ELECTRIC LIGHTING

A

PRACTICAL EXPOSITION OF THE ART

FOR THE USE OF

ENGINEERS, STUDENTS, AND OTHERS INTERESTED IN
THE INSTALLATION OR OPERATION OF
ELECTRICAL PLANTS

VOLUME I.

THE GENERATING PLANT

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PREFACE.

ELECTRIC LIGHTING having now become one of the most important branches of applied science, there is a demand for information on the subject. This demand is by no means confined to electrical engineers, but applies also to mechanical, mining, and other engineers, architects, fire underwriters, students in colleges and technical schools, lawyers and business men who may be called upon to consider questions relating to electric lighting. But the development of this art has been so very rapid, and so many changes and improvements were continually being made, that heretofore any attempt at a complete treatise on the subject would become out of date while it was being printed.

There are already good elementary works on electric lighting; and in the case of special branches, such as the dynamo, transformer, electrical distribution, etc., we have several excellent books; but none of these cover electric lighting as a whole, or what might be called electric-light engineering.

The author believes that the time has now arrived, however, when electric lighting has reached a sufficiently perfected and established state to allow of its being treated in a fairly satisfactory and permanent manner.

The apparatus and methods now employed are almost as well standardized as in other arts. The dynamo, which is the most important element, is one of the most perfect machines in existence. Arc and incandescent lamps, overhead and underground wires, transformers, and almost all the other parts of electric-lighting plants, have also become sufficiently stereotyped. In fact, it is remarkable that of all the important features of an electric-lighting system, the steam-engine is the one which is now being modified to the greatest extent, although it is, of course, much older than the others.

The plan adopted in this book is to follow the usual sequence

in which the electric current is generated, transmitted, and utilized in electric lighting. That is to say, the introductory principles are first given; then the building, boilers, engines, dynamos, distributing conductors, lamps, etc., will be considered in the natural order in which the electrical energy is first obtained, and finally converted into light in the lamps. The attention of the reader is particularly called to this arrangement, which is given in full in the Table of Contents. This order not only facilitates the understanding and remembering of the various parts of the subject, but also enables one to quickly turn to any particular part without using the Table of Contents or Index, since one knows without any effort of memory the position of each element with reference to the others.

The entire subject of electric lighting naturally divides itself into two parts; one relating to the generating-plant, and the other covering the distributing conductors, lamps, special applications, etc. The present volume is confined to the first part, leaving the other matters to be included in a second volume. It is impracticable to give descriptions of typical plants in this volume, since a knowledge of electrical distribution would be required to understand them, hence they will be put in the second volume. But the attempt has been made to explain nearly all of the important elements or methods employed in an electrical generating-plant. The apparatus used in an electric railway or power station, or even in an electrometallurgical generating-plant, are so similar to those adopted in electric lighting that the following pages are for the most part applicable to them also.

In many courses of instruction the subject of steam- and gas-engines, water-wheels, and other purely mechanical matters, are not included in the lectures on electric lighting, being taught by other instructors as entirely distinct matters. In fact, the author approves of this plan himself; nevertheless, for completeness, it was deemed proper to incorporate the mechanical subjects with the electrical ones, and to consider particularly their application to electric lighting. These portions of the book will at least serve as a review or memorandum of what it is essential to know, even though the knowledge has already been acquired elsewhere.

It is quite a common fault in technical books that many of the machines and methods given as examples are either untried

or abandoned experiments. We find elaborate drawings and descriptions of apparatus that never operated successfully, or was never even built; and other machines which work admirably, and of which hundreds may be in use, are not mentioned at all. In the following pages the endeavor has been to give the most prominent modern and typical cases as examples; and doubtful or less important instances are merely mentioned, or references to books or papers which describe them are given for the sake of completeness, and to facilitate the special study of any particular subject. In fact, references are inserted very freely throughout the book, because they are often of great help, and do no harm if the reader does not care to follow a subject farther.

The author desires to express indebtedness to his former pupils, Messrs. C. H. Parmley and Max Osterberg, whose carefully taken notes of his lectures formed the basis of this work; to Professor R. B. Owens of the University of Nebraska for ideas on the location of a station (Chapter V.); to Professors M. I. Pupin and F. R. Hutton, Mr. E. A. Darling and Mr. G. F. Sever of Columbia University for proofreading and suggestions in regard to the steam-engine, dynamo, etc. (Chapters VIII. to XVII.); also to Mr. Gano S. Dunn and Mr. D. R. Lovejoy for proofreading.

The author also takes this opportunity to thank the manufacturers and engineers who have kindly furnished information as well as illustrations. In nearly all cases the sources from which these have been obtained are stated in the text or in the titles of the figures.

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ELECTRIC LIGHTING.

CHAPTER I.

INTRODUCTION.

ELECTRIC LIGHTING is the art of producing artificial illumination by means of electrical energy.

Generally speaking, an electric lighting system comprises three essential elements, viz.: —

1. *Apparatus for generating the electrical energy*, for which purpose dynamo-electric machines driven by steam or gas engines or water-wheels are almost universally employed.

2. *Means for transmitting and distributing the electrical energy*, which consist largely of copper conductors.

3. *Devices for converting the electrical energy into light*, which are practically always either arc or incandescent lamps.

In addition to these three essential elements, certain auxiliary devices are commonly employed, such as transformers, secondary batteries, switching, regulating, and measuring apparatus, etc.

The words *system*, *installation*, and *plant* are all used to designate the collection of apparatus and other elements employed for electric lighting in any given case. The first term is used too freely; as, for example, when some trifling device is called "a new system of electric lighting." Nevertheless, these terms have their legitimate use in discussing electric lighting. Their significance in this connection is substantially identical with their ordinary meaning.

The dynamo-electric machines used in electric lighting are the various well-known forms of mechanical generators of electricity. They may be defined as machines for converting mechanical energy into electrical energy; or, in other words, they generate electric currents when driven by mechanical power.

The term dynamo-electric machine is so long that it is usually and almost unavoidably shortened into "dynamo," which

has exactly the same meaning. The name "electric generator," or simply "generator," is often applied to the dynamo, especially when it is used to produce current for electric railway or other motors; but this distinction is merely for convenience. An alternating current dynamo is commonly called an "alternator."

Two essentially different kinds of electric currents are in use, *direct* and *alternating;* and the differences between them give rise to very important variations in the construction and operation of electric-lighting plants.

A direct or continuous current flows in one direction only; whereas an alternating current reverses its direction of flow, and usually the reversals occur very rapidly, that is, 50 to 266 times per second, the "frequency" or number of *complete periods* being between 25 and 133 per second in all systems in general use.

The steam or gas engines and water-wheels employed in electric lighting are practically the same as those used for other purposes, except that it is especially important that they should be very constant in speed.

Steam and gas engines and water-wheels being practically the only prime movers or sources of mechanical power used in electric lighting, are quite fully treated in Chapters VII. to XIV. inclusive.

The mechanical connection between the engine and dynamo is a matter of much consequence; in fact, it has been the cause of considerable trouble and discussion in electric-light engineering, and it therefore receives particular attention in Chapters XV. and XVI.

The dynamo being by far the most essential element in electrical engineering is treated in considerable detail. Chapter XVII. is devoted to the principles and construction of dynamos, Chapter XVIII. to typical forms, and Chapter XIX. to the practical management of these machines. The last subject is certainly of fundamental importance in electric lighting; and no fact concerning it, however small, is unworthy of consideration. Indeed, to nearly all electric-light engineers a knowledge of the construction of the dynamo is chiefly useful because it enables them to manage these machines more intelligently, and not because they are called upon to design or build them.

Accumulators are often used in connection with the generating-

plant. An accumulator, also called a secondary or storage battery, consists of a number of voltaic cells containing plates or electrodes and a conducting liquid or electrolyte. Such a battery is inert in itself; but, on passing a current through it, certain chemical changes are produced, which render it capable of afterwards reproducing a large fraction of the electrical energy put into it.

In Europe accumulators have been more extensively and successfully employed than in the United States, but they are now being quite rapidly introduced into central stations and isolated plants in this country.

The principles, construction, and action of accumulators are discussed in Chapter XX.; and their use in electric lighting is considered in Chapter XXI.

Switchboards, including measuring instruments, switches, circuit-breakers, fuses, automatic cut-outs, rheostats, ground detectors, and other similar apparatus, are described in Chapters XXII. and XXIII.

Lightning arresters, which involve almost the only very uncertain questions in electric lighting, are carefully considered in Chapter XXIV.

This completes the list of elements which form part of the generating-plant; and the remainder of the subject, comprising the distribution and utilization of the electrical energy, is to be included in a second volume, to follow the present one. It is impossible to consider the generating-plant as a whole in this volume, since a knowledge of the distributing-conductors, lamps, etc., is essential to an intelligent general view of the station. This extremely important matter will therefore be reserved for the second volume, which will also include underground and overhead conductors, transformers, recording-meters, house-wiring, arc and incandescent lamps, applications of electric lighting, general management, finance, etc.

ADVANTAGES AND DISADVANTAGES OF THE ELECTRIC LIGHT.

Before entering upon the detailed study of electric lighting, certain general questions present themselves for consideration. In the first place, the relation of the electric light to other forms

of artificial light is a matter upon which its ultimate success or failure necessarily depends. In other words, if the electric light does not possess decided advantages over the gas light and other means of lighting already in existence, it is obvious that its introduction is of no utility, and the study of it is unnecessary. In short, the very existence of the electric light in practical use depends upon its exact value compared with that of its rivals; and therefore it will be well to carefully consider its various advantages and disadvantages.

The marked advantages of electric light over gas light may be enumerated as follows: —

1. It does not vitiate the atmosphere; * that is, it neither consumes the oxygen upon which the life and health of human beings depend, nor produces carbonic acid or other gases which are deleterious.

2. It is much cooler; i.e., it produces less than one-tenth as much heat for the same amount of light.

3. It can be lighted without the aid of matches, which is not only a great convenience, but also largely reduces the danger of fire.

4. The incandescent light is much steadier than gas light, and does not flicker even in a strong current of air.

5. The incandescent lamp itself is practically free from the possibility of setting fire to anything, because the source of light is hermetically sealed in a glass globe; and even if the globe is broken in a barrel of gunpowder or kerosene, it will not ignite them.†

6. The lamps are capable of much more convenient and æsthetic arrangement; that is to say, lamps can be put close against a wall or ceiling, or they can be placed pointing upward or downward, or inclined at any angle, all of which arrangements are impossible in the case of gas or other kinds of lamps.

7. The lamps can be lighted and controlled from any desired point. For example, the switch may be placed at the entrance of a building or room.

* This is strictly true only of the incandescent lamp, but it practically applies to the arc lamp also.

† A mixture of explosive gases, however, might be exploded in this way. But this danger is largely avoided by inclosing the lamp in a thick glass globe.

8. Incandescent lamps can be obtained of any power, from a small fraction of one candle-power up to several hundred, and one can be substituted for the other in a few seconds, which is not practical with any other means of illumination.

It should be remarked that the above advantages apply more particularly to the incandescent electric light than to the arc light; but the former is the one used almost entirely for interior illumination, the latter being used more for street lighting and other rougher uses, where fine points of advantage are not of so much consequence.

The only disadvantages of the electric light to offset the numerous and important advantages stated above are: —

1. The electric light cannot be turned down like a gas or oil lamp.

This objection is often urged; but it amounts to very little, because it is rarely desirable to turn down a light, and ninety-nine times out of a hundred when it is done it is to save the trouble of relighting. To avoid danger of fire, and for other reasons, it is ordinarily a positive advantage to turn out a light entirely when not required; and this can be done in the case of the electric light without involving any trouble in relighting it.

Furthermore, the incandescent light can be dimmed, if desired, in several ways. A resistance can be used for a direct current, and a choke coil for an alternating current; and either of these can be applied without much trouble or expense, and the only reason they are not often used is that they are not needed. For a sick-room, or other place where a dim light is required, a low-candle-power lamp can be employed, or the light can be shut off by a shade or screen.

2. It is often stated that the electric light has an injurious effect upon the eye. The intense glare and usual unsteadiness of an arc light are often unpleasant, and would probably be harmful to the eye if exposed to it for any length of time. But the arc lamp is generally used for lighting streets, halls, railway stations, and other places where sight is general, and not applied to small objects. For lighting small spaces, or for any case where reading, writing, or other fine work has to be done, the arc light should be shaded, or arranged so as not to throw its glare directly into the eye.

The incandescent light seems to be steadier than any other kind of light; but the author has heard of, or actually observed, cases where sensitive eyes were disagreeably affected by it. The slight fluctuations in speed and current due to the strokes of the engine often produce a perceptible flickering in the lights, which can best be detected by holding a piece of white paper close to the lamp. This can be overcome or reduced by higher speed or heavier fly-wheels, and certainly should be brought down until it is imperceptible. Two or more engines or dynamos working on the same circuit might shift the load from one to the other, or otherwise act unharmoniously. This would be more likely to occur with alternating currents which might surge back and forth, due to lack of perfect synchronism or equality of action in the generators. The sudden throwing on or off of motors or a considerable number of lamps, the intermittent slipping of a belt or inductive action between two or more alternating currents differing slightly in phase, are also causes of variation in lamps which should be guarded against.

3. The incandescent light is sometimes more expensive than gas light; but this is by no means always the case, especially in large, isolated plants in hotels, factories, etc., where boilers, engines, and engineers are required in any case, so that the *extra* expense due to the electric light is small, and its cost is actually less than the same amount of light obtained from gas. For more exact comparisons of the cost of electric light and gas, the reader is referred to volume 2, chapter on management, which deals with the financial aspects of electric lighting.

As a matter of fact, however, the real importance and utility of the electric light is dependent upon its radical advantages over any other form of artificial light; and whether it costs a little more, a little less than, or exactly the same as, gas light, is not so very important. For example, gas light costs more than lighting by kerosene lamps; but the greater convenience and general superiority of gas are sufficient to practically eliminate the use of kerosene wherever gas is available. The advantages of the electric light over gas are similar in character to, and fully as great in degree as, the advantages of gas over oil; and this applies to the Welsbach burner and acetylene gas as well as to ordinary illuminating-gas. The advantages of the incandescent lamp

stated above, particularly the facts that it does not vitiate the atmosphere or produce as much heat, and can be lighted without matches, make it a superior kind of light in practically every respect; and it is probably a fact in nearly every case where electric light is introduced instead of gas, that this is the reason, and not because it is expected to be cheaper than gas. This, however, is only true when the cost of electric light is approximately equal to that of gas. If the cost were very much greater, it would prevent its use in many cases. If, on the other hand, electric light is actually cheaper than gas, in addition to its other decided advantages, then there would appear to be no reason why it should not be used almost universally wherever it can be obtained.

In this connection, it should be noted that the manufacture of much cheaper and also better engines and dynamos, as well as other apparatus, more advantageous arrangement of plants, and decidedly improved technical and business management, all tend to reduce the cost of electric lighting.

At the present time it costs about one cent per hour for each lamp of 16-candle power (about 55 watts), supplied from a central station. In certain places, or for a large number of lamps, this charge is as low as one-half of one cent; or, in other words, the price for central-station incandescent lighting is between one-half and one cent all over the world. This is equivalent to ordinary illuminating-gas at one to two dollars per thousand cubic feet, which are the usual limits of price. In an isolated plant, put in where a steam plant already exists, the *additional* expense is small, as explained above; and the author knows of cases * where the cost is only one-seventh of one cent per lamp-hour. Even if the electric light be charged with its share of all expenses, it can be produced for .2 to .25 cent per lamp-hour, provided the average load is at least 400 or 500 lamps. One of the chief reasons why isolated-plant lighting can be made cheaper than central-station lighting, is the saving of the vast system of distributing conductors, the interest on and maintenance of which is usually the largest item of expense of an electric-light company.

* "Comparison of Cost of Electric Lighting at Columbia College by Isolated Plant and by Contract with Central Station," *School of Mines Quarterly* (N. Y.), vol. xiv., *Elec. Review* (Lond.), 1893.

CHAPTER II.

HISTORY OF ELECTRIC LIGHTING.

LIGHTNING is the first and grandest form of electric light. Ordinarily, however, we confine the term to mean artificial electric light. Considered from this point of view, probably the first electric illuminating effects obtained by man were electric sparks produced intentionally or accidentally by frictional electricity. The effects obtained, however, in these very early experiments were so feeble that they are hardly worth considering ; and it was not until the first electrical *machine* was made by Otto von Guericke, about the middle of the seventeenth century, that the sparks produced were sufficiently powerful and frequent to be looked upon as even the germ of the electric light. In fact, the duration of an electric spark being only an almost infinitesimal fraction of a second, it can hardly be considered to be a light of any practical use. Later, however, the frictional electric machine was improved by Newton and others, and numerous experimenters took up the study and development of electricity. One line of work which probably produced an electric light worthy of the name earlier than any other method, and one which has recently assumed particular importance, is the production of light by means of electrical *discharges* in air or other gases, whether rarefied or not. Intermittent electric sparks are entirely too sudden and temporary, unless the number of sparks is made sufficiently great to be practically equivalent to a continuous discharge.

During the latter part of the seventeenth and early in the eighteenth century numerous experiments were made with discharges in air or rarefied gas.

The record of these may be found in a book entitled *Physico-Mechanical Experiments on Various Subjects, containing an Account of Several Surprising Phenomena touching Light and Electricity.* By F. Hauksbee, F.R.S. Published in London in 1709.

The above experiments deserve to be considered as being the first production of the electric light in anything like a practical

way, although heretofore they have been ignored so far as the history of electric lighting is concerned; but the interesting experiments of Tesla and others in connection with electrical discharges might lead us to look upon these very early attempts as being as important as much later experiments which are ordinarily given as the origin of the electric light. Leaving aside, however, the question of what the electric light of the future may be, it is certainly a fact that the electric light of the present day depends essentially upon the use of an electric *current* of several amperes, or a large fraction of one ampere. Frictional electric machines cannot give any such current; therefore electric lighting of the kind now practiced was an impossibility until some source of electric current was discovered. The first source of this kind was the primary battery, or chemical generator of electricity, invented by Volta in 1800. The voltaic battery was soon taken up and developed by scientific men, and batteries of sufficient power to produce quite strong currents were made by Volta himself and by others. Sir Humphry Davy immediately recognized the great possibilities of the battery for scientific and practical use, and constructed a very large one of 2,000 pairs of plates in 1808. This battery was used by him in various investigations; and in the years of 1809 and 1810 he performed with it the epoch-making experiment of producing a continuous and brilliant electric light, which was practically identical in principle with the arc light of to-day. This experiment is best described in his own words as follows: "When pieces of charcoal about an inch long and one-sixth of an inch in diameter were brought near each other, within a thirtieth or fortieth part of an inch, a bright spark was produced, and more than half the volume of charcoal became ignited to whiteness; and by withdrawing the points from each other a constant discharge took place through the heated air, in a space equal to at least four inches, producing a most brilliant ascending arch of light."

It should be noted that in the above experiment Davy made use of *carbon* electrodes, which are the essential elements of the present arc lamp; and carbon is also used for the filament of all practical forms of incandescent lamp. He also noticed the arched form of the electric current between the carbon points, from which form the arc derives its name. This great experiment is unques-

tionably the foundation of the present methods of electric lighting; but the use of a voltaic battery as the source of current prevented any extensive introduction of the electric light, on account of the prohibitive expense and trouble of running a battery large enough to give sufficient current. A much more powerful and cheaper source of electrical energy was needed to make the electric light a practical success; therefore little or no progress was made until the discovery by Faraday, in 1831,* of magneto-electric induction, which was almost immediately followed by the rapid development of the magneto-electric machine, or mechanical generator of electricity, from which has been evolved the modern dynamo-electric machine. The most notable of the first machines were those of Dal Negro,† Pixii, ‡ Saxton (1833), § and Clarke (1835).‖ These machines were all similar in principle, and consisted essentially of coils or bobbins of copper wire and a permanent magnet, one of which was revolved and the other held stationary. This rotation produced primarily an alternating current in the coils, which was led out by suitable connections. At the suggestion of Ampère,** a commutator was added, in order to obtain a direct current; that is, one flowing in one direction only. These magneto machines were perfected and built on a larger scale by other experimenters.

The most noteworthy types of these larger machines were the "Alliance machine" and the "Wilde machine." These forms were made of considerable power; that is to say, they were capable of generating currents of several horse-power, and adapted to being used for practical work. The Alliance machine originated with Nollet in 1849, and was improved by Holmes, Masson, Du Moncel, and others; and in 1857 it had been brought up to a fairly perfected condition. In 1863 this machine was applied to lighting the lighthouses of the French coast by electricity. This was probably the first important *practical* use of the electric light, and is therefore of great interest. About the same time the Wilde machines were also being used to generate current for arc lights; but these for the most part were for experimental or exhibition purposes. These machines, it should be

* *Experimental Researches*, vol. i. p. 25. † *Phil. Mag.*, July, 1832.
‡ *Ann. Chim. Phys.*, vol. l. p. 322, 1832. § *Phil. Mag.*, 1836. ‖ *Ibid.*
** *Ann. Chim. Phys.*, li., 76, 1832.

remembered, were up to that time of the magneto type; that is to say, the field magnetism was produced by permanent magnets. The use of electro-magnets, and the principle of self-excitation as applied to the modern dynamo-electric machine, was developed by various workers. In 1845 Wheatstone and Cooke patented the use of electro-magnets instead of permanent magnets, which were, however, to be excited by a current obtained from some source outside of the machine itself, being what is now called separately excited. Brett, in 1848, suggested that the permanent magnetism in a magneto machine might be increased by the current of the machine itself. Sinsteden independently made a similar suggestion in 1851. Wilde, in 1863, used a small magneto machine to supply currents to an electro-magnet which formed the field magnet of a very much larger generator. In this way he obtained very powerful effects, and made a machine capable, for example, of fusing a copper rod of considerable diameter. The definite and complete invention of the principle of using the current of the machine itself to feed its own field magnet was independently and almost simultaneously announced by Werner Siemens to the Berlin Academy on Jan. 17, 1867, and by Sir Charles Wheatstone to the Royal Society of London on Feb. 14, 1867. This gave to the world the modern dynamo-electric machine, upon which, more than anything else, the great success of electric lighting and almost all the other applications of electricity depends. The next important step in the development of the dynamo was the improvement of the armature, which up to that time had been quite crude. In 1860 Pacinotti designed, and in 1865 published* a description of, a machine having a ring armature with a continuous winding. This is the essential element of the very high efficiency direct-current generators of the present day. This invention was practically ignored until it was independently rediscovered by Gramme in 1870.

The invention of Pacinotti had been merely a laboratory experiment, whereas Gramme took up the subject as an engineer, and designed and constructed many successful machines of this type. In 1873 von Hefner-Alteneck applied Gramme's principle of a continuous or closed-coil winding to the shuttle armature invented

* *Nuovo Cimento*, xix., 378, 1865.

by Werner Siemens in 1856. The Siemens shuttle armature, sometimes called the I armature on account of the form of cross section of its iron core, was at the time of its invention a decided improvement over the bobbin forms of armature then in use in regard to mechanical construction and compactness; but in its magnetic and electrical action it is radically imperfect, principally because it has only a single coil, which produces a very intermittent effect. The Alteneck armature, on the other hand, is wound with a number of coils or sections of wire in different planes, and is therefore continuous and steady in its action, like the Gramme armature. The only difference in principle between these two important types of armature is the fact that the iron core of the Gramme armature is in the form of a ring, while that of the Alteneck armature is a drum or cylinder. In fact, these terms are more commonly employed to designate the two types of armatures than the names of their inventors. Up to that time the history of electric lighting had been the history of the electric generator, because a good source of current had first to be obtained before any real progress could be made in applying electricity to the purpose of lighting. But the dynamo machine having been brought up to a reasonably practical form, it was available to form a solid basis for the astonishingly rapid development of practical electric lighting which then began. At the same time that the dynamo was being improved the problem of producing a satisfactory electric lamp was also being grappled with; but no very successful results had been obtained. Serrin in 1857, and others, had constructed arc lamps, or what were then called "regulators," which consisted of the electric arc between carbon points such as was produced long before by Davy, with the addition of a clock-work or other mechanism for feeding the carbons together as they burned away.

The incandescent lamp progressed at first even more slowly and imperfectly than the arc lamp. Crude forms of lamps were devised and made by Starr and King in 1845, Staite in 1848, and others; but none of these attempts can be looked upon as anything more than interesting experiments which laid the foundation for further progress. In 1876 there existed fairly satisfactory forms of dynamo machines and of arc lamps, and there

were crude forms of incandescent lamps ; but up to that time the work that had been done consisted of separate and incomplete experiments. What was lacking was a *complete* set or system of apparatus which could be used to produce electric lighting in a practical way, or rather *commercial* way. This putting together of the necessary elements, even though they may already exist separately, is often a more important and difficult step in the creation of a new art than the invention of the individual parts, however essential each may be. In 1878 and 1879, the times being in that peculiar state when they are ripe for very rapid advance, which condition usually precedes all great inventions or industrial enterprises, there occurred almost simultaneously the bringing forth of several more or less complete systems of electric lighting. At that time the most serious difficulty was the so-called "subdivision" of the electric light; that is, the running of several lamps from the same source of current, or on the same circuit, without interfering with each other. This bugbear was greatly exaggerated, and was much discussed by scientific and technical men at that time, some of whom maintained that the subdivision was not only practically but theoretically impossible. The overcoming of this difficulty was therefore the primary object of the electric-lighting systems first introduced. Three radically different methods were almost simultaneously brought out, and put into quite extensive practical use. These three systems were invented and developed by Jablochkoff of Paris; Brush of Cleveland, O.; and Edison of Menlo Park, N.J. In the Jablochkoff system the subdivision of the electric light was accomplished by using a form of lamp called an electric candle, which was first invented by him in 1876. It consists of two thin pencils of carbon held at a fixed distance apart by insulating material in the form of a strip of kaolin. All that was necessary to operate a number of these lights on the same circuit successfully was to connect them by wires in a simple series, so that the current flowed through them one after another. The arc formed at each lamp was necessarily of constant length, and there was no tendency for one lamp to act differently from the others, or interfere with them in any way. An alternating current dynamo was employed to supply the current, in order that the two pencils should burn at the same rate. The Jablochkoff system has the

practical difficulties of requiring a new candle to be switched on every two hours, and the cost of the candles made the light rather expensive. It was sufficiently developed to be used for lighting the Avenue de L'Opéra and other places in Paris in 1878, and it was also introduced and used in a few places in America; but the objections stated above prevented it from being a permanent success commercially.

In the Brush system, brought out in 1878, arc lamps with regulating mechanism practically identical with those employed to-day were operated in series on a single circuit. The success of this system was due to the fact that it included a complete set of apparatus; that is, a dynamo having a current regulator, and arc lamps with differential coil regulators and simple ring-clutch mechanism, which lamps could be operated satisfactorily in series. Brush also invented the "double-carbon" lamp; that is, a lamp in which a second pair of carbons are automatically thrown into action when the first pair are used up. This form of lamp is practically essential whenever it is necessary to run all night, which is, of course, required in the case of most street-lamps. In short, Brush gave to the public a system in which the various elements were reasonably good in themselves, and co-operated to produce a fairly economical and generally satisfactory method of lighting. Good business management also contributed largely to the wide use and original success of the Brush apparatus.

The Edison system, which was developed experimentally during 1878–1879, and brought out commercially in 1880, made use of the incandescent instead of the arc lamp. The Edison system contained the necessary elements for a successful use of the incandescent lamp, which elements had not been known or used previously, although the system is apparently very simple. These essential elements are: First, a dynamo having an armature with a very low internal resistance; and the armature introduced by Edison did not have more than one-fifth to one-tenth of the resistance of similar machines used by others prior to that time. Second, a constant potential or electrical pressure was maintained throughout the system of conductors, to which the lamps were connected in parallel, that is, in branch circuits, so that the turning on or off or breaking of a lamp did not affect the others. Third, the lamps consisted of high-resistance carbon filaments

hermetically sealed in glass globes in an almost perfect vacuum. High-resistance filaments are practically necessary to enable the use of reasonably high voltage, which greatly reduces the weight of copper required for the conductors, and a vacuum is required to prevent the destruction of the filament and the loss of heat by convection. At the same time that the Edison system was brought out, or soon after, other inventors were working on systems similar to the above. Important contributions to the progress of incandescent lighting were made in lamps and other devices by Sawyer and Man, Maxim and Weston, in America; also by Swan and Lane Fox in England. In the field of arc lighting, Thomson and Houston brought out a complete and very successful system, which had the radical advantage over the Brush system that the regulator for controlling the current and keeping it constant was superior to that employed by Brush. Indeed, the great success of the Thomson-Houston system was largely due to the very ingenious and effective regulator which they applied to their dynamo. Another arc-lighting system was brought out by Weston; but this also was defective in not having a satisfactory current regulator, although the dynamo and lamp were exceedingly well designed and constructed, considering the time at which they were made. In Europe, arc-lighting systems have been developed by Siemens, Krizig & Piette (the "Pilsen lamp"), Crompton, Gulcher, and other inventors and manufacturers; but arc lighting in Europe has never been particularly popular or extensively used even up to the present day.

A system of electric lighting by means of alternating current transformers was invented by Gaulard and Gibbs in 1882. This system was based on the early experimental work with induction coils by Faraday in 1831, Henry in 1832, Page in 1835, Sturgeon in 1837, Ruhmkorff in 1851, and others. Gaulard and Gibbs made the fatal error of running the transformers in series, which is impracticable. In 1885 Zipernowsky, Deri, and Blathy brought out a system in which this mistake was corrected, the transformers being worked in parallel. The alternating current transformer system was extensively and successfully introduced in the United States in 1887 by the efforts of Westinghouse, Stanley, and others. The great saving in the amount of copper required for the distributing conductors in this system caused it to be

rapidly and widely adopted. In the meantime, the dynamo machine was being gradually but steadily perfected by the various inventors and manufacturers, for use in their electric-lighting systems. Edison, Brush, Thomson, Houston, and Weston, all contributed to this progress. The multipolar dynamo was developed by Elphinstone and Vincent in 1879 and 1880, and by Schuckert, Gramme, Gulcher, Mordey, and others. The theoretical study of the dynamo was taken up by Clausius, Sir William Thompson, and Frölich. The last-named brought out in 1880 a working theory which is still of practical value. A great advance in the theory and practical design of dynamos was made by J. and E. Hopkinson in 1886.* Their paper laid down the correct theory, and embodied a method of designing the magnetic circuit of dynamo machines, which up to that time had been very imperfectly understood; and most machines at that time were very bad in this respect. Kapp brought out in 1887 a similar method of designing the field magnets of dynamos; but it was largely empirical, and not so complete and scientific as the Hopkinson method, which is now generally used by the best electrical engineers. Hopkinson and Edison † independently invented the three-wire system of distribution, which makes a considerable saving in the amount of copper required for low-tension circuits. Incandescent lamps have gradually been improved in cheapness and efficiency, and the mechanism of arc lamps has been perfected from time to time. Great improvements have been made in the last few years in the construction of large direct-coupled steam-engines and multipolar dynamos for central stations. Enormous progress has also been made in the general perfection of the various details of electric-lighting plants. The insulation of electrical conductors has been very greatly improved. Secondary batteries have been extensively applied to electric-light stations and isolated plants in Europe; in America, however, they have not been very largely or successfully employed, but their use is now becoming more general. This progress has, for the most part, been made by comparatively small advances at any one time, and nothing very radical can be mentioned. The recent work of Tesla in connection with high-frequency and high-potential alter-

* *Philosoph. Transact. of the Royal Society.*

† U. S. Patent No. 274290, March 20, 1883.

nating currents to produce electrical discharges in air and in vacuum tubes is highly interesting and suggestive, and there is reason to hope that electric-lighting systems based upon such principles may be developed in the future. In fact, this would seem to be the principal direction in which to look for every considerable progress, especially with lamps of much higher efficiency.

For further study of the general history of lighting, the reader is referred to the following: —

Histoire du Luminaire depuis l'époque romaine jusqu'au XIXe. Siècle, par Henri-René D'Allemagne, Paris, 1891.

This is a voluminous treatise on the history of all methods of artificial illumination from ancient to modern times, and contains hundreds of fine illustrations. The artistic side is most prominent, but technical matters of construction and operation are also considered.

For the history of electric lighting reference may be made to *The Electric Light*, by Alglave and Boulard; translated by T. O'Conor Sloane; edited by C. M. Lungren. This gives the history of electric lighting quite fully, particularly the apparatus and the methods first introduced.

Electric Illumination, by James W. Dredge, two vols., London, 1883–1885, contains the most complete account of the history of electric lighting prior to the dates of publication, each form of dynamo and lamp being described in detail.

Arc and Glow Lamps, by Julius Maier, London, 1886, contains illustrations and descriptions of many forms of lamps which have been or are now used. *The Evolution of the Electric Incandescent Lamp*, by F. L. Pope, Elizabeth, N.J., 1889, gives a detailed account of the early work of Sawyer and Man, and Edison. Marsden J. Perry gave an address on the history of electric lighting before the National Electric Association, February, 1891 (*Elec. World*, Feb. 28, 1891); and Charles F. Brush gave very interesting personal reminiscences of the early history of arc lighting before the same body in February, 1895 (*Elec. World*, March 2, 1895).

A very complete history of the dynamo is contained in Thompson's *Dynamo-Electric Machinery* (Fourth Edition, pages 6–21), in which exact references to original publications are given.

CHAPTER III.

GENERAL UNITS AND MEASURES.

THE general principles of electricity should first be studied and understood before one attempts to take up the subject of electric lighting or other branch of electrical science, whether theoretical or applied. In electrical books it has been a common practice to devote a great deal of space to first principles; in fact, it is no exaggeration to say that from one-quarter to one-half of almost every book which treats of some particular branch of applied electricity is taken up by a discussion of the elementary facts of electricity and magnetism. The result has been that the first parts of almost all electrical books are practically identical, and the subject itself is hardly touched until nearly one-half of the space has been used up, which greatly curtails the real subject-matter. This practice is obviously unnecessary, and most readers skip the first part before they find anything that interests them. The source from which to obtain a sufficient knowledge of the fundamental principles is some elementary or general treatise; and the reader, if not already familiar with the subject, is referred to such treatises, and recommended to acquire a general knowledge of electricity before attempting to master electric lighting or any other application of electricity. There are, however, certain important facts and principles which are of special significance in connection with any particular subject.

Furthermore, there is a certain amount of choice in the selections of units, standards, terms, and definitions, which make it desirable for each author to specify exactly which of these he employs; otherwise, considerable confusion and uncertainty might arise in the mind of the reader, because different authors employ quite different standards, terms, etc. There is, fortunately, a strong tendency towards uniformity and definiteness in regard to electrical units and terms, and each year sees considerable advance in this direction. The most important example of this is the universal adoption of the "International" volt, ohm, and other electrical

units, which are no longer abstract, as they formerly were, but are concrete and material standards. We have, on the other hand, quite a large increase in the number of electrical terms and units, due to the rapid progress of knowledge; but such new terms must necessarily be experimental and unsettled until they are found to be not only correct, but useful. In fact, the test of utility alone largely determines the question of whether a new term or unit is worthy of adoption. The outcry against the introduction of any new electrical term is futile, because they are the inevitable result of progress and more exact knowledge. The simple fact is, that the time is soon coming when no one person can be master of more than one or at most a few branches of electricity. On the other hand, the multiplication of new units and terms can be, and often is, carried too far. It is not desirable to have a name for every possible quantity or combination of quantities, and it is still more superfluous to give names to the *reciprocals* of all these quantities. Such matters, however, take care of themselves, and time will show what is necessary or desirable. It may be the duty of future electrical congresses to abolish units and terms which are found to be useless.

In the present work it was thought best to put the various principles with the particular subject to which they naturally belong; for example, the data of electromagnetism are given in connection with the dynamo. There are, however, certain fundamental units which are used in many branches, and a few of these are given in this chapter for convenience. The necessity for this is increased by the unfortunate fact that both the metric and English systems of measure are used in electrical engineering; and we are practically forced to use both, and often the two systems are actually mixed in the same sentence! Hence the ratios for converting one system into the other are often needed.

There seems to be no way to avoid this at present, and the transition must be made gradually. Indeed, it will be extremely difficult to change the measurements of wires, machines, etc., which are always manufactured and measured in terms of inches and feet. But in some cases the use of centimeters and other metric units involves no serious trouble, and the centigrade thermometer scale can often be substituted for the senseless Fahrenheit scale, thus accustoming ourselves to the change.

In steam-engineering, however, the English system is still employed almost exclusively, and in many cases we must even use Fahrenheit heat units in order to be understood. It does more harm than good to attempt to force these matters; and a book in the English language which uses one system exclusively is very inconvenient to a large fraction of its readers, and is not suited to the present times.

The following tables are given to facilitate the conversion of metric into English units, or *vice versa*. The logarithms (six-figure) of each number are also given. In most cases four-place logarithms are sufficiently accurate; hence a space is left between the fourth figure and the last two, so that the latter may be easily omitted. Approximate values for mental calculations are given in many instances, the error being usually less than one per cent.

MEASURES OF LENGTH.

	APPROX. VALUE.	ACTUAL NUMBER.	LOGARITHM.
Millimeters in one inch	25	25.4	1.4048 34
Centimeters in one inch	$2\frac{1}{2}$	2.54	.4048 34
Centimeters in one foot	$30\frac{1}{2}$	30.48	1.4840 15
Meters in one foot	$\frac{4}{13}$	.30480	$\bar{1}$.4840 15
Meters in one yard	$\frac{11}{12}$	.91440	$\bar{1}$.9611 36
Meters in one statute mile		1609.35	3.2066 50
Kilometers in one mile	$1\frac{3}{5}$	1.60935	.2066 50
Inches in one centimeter	$\frac{2}{5}$	.3937	$\bar{1}$.5951 65
Inches in one meter	$39\frac{3}{8}$	39.37	1.5951 65
Feet in one meter	$3\frac{1}{4}$	3.28083	.5159 87
Feet in one mile		5280.	3.7226 34
Feet in one kilometer		3280.83	3.5159 87
Yards in one meter	$1\frac{1}{11}$	1.09361	.0388 65
Yards in one mile		1760.	3.2455 13
Miles in one kilometer	$\frac{5}{8}$	.62137	$\bar{1}$.7933 50

MEASURES OF AREA.

	APPROX. VALUE.	ACTUAL NUMBER.	LOGARITHM.
Square millimeters in one square inch		645.16	2.8096 68
Square centimeters in one square inch	$6\frac{1}{2}$	6.4516	.8096 68
Square centimeters in one square foot		929.03	2.9680 30
Square meters in one square foot	$\frac{1}{11}$	.092903	.9680 30
Square kilometers in one square mile	$2\frac{3}{5}$	2.59	.4133
Square inches in one square centimeter	$\frac{2}{13}$	.155	$\bar{1}$.1903 32
Square inches in one square meter		1550.	3.1903 32
Square feet in one square meter	$10\frac{3}{4}$	10.764	1.0319 74
Square yards in one square meter	$1\frac{1}{5}$	1.196	.0777 31
Square miles in one square kilometer	$\frac{2}{5}$	.3861	$\bar{1}$.5867

MEASURES OF VOLUME.

	APPROX. VALUE.	ACTUAL. NUMBER.	LOGARITHM.
Cubic centimeters in one cubic inch	$16\frac{2}{5}$	16.387	1.2145
Cubic centimeters in one cubic foot		28316.	4.4520 30
Cubic meters in one cubic yard	$\frac{3}{4}$	.7645	$\bar{1}$.8833 77
Cubic inches in one cubic centimeter	$\frac{1}{16}$	.06102	$\bar{2}$.7854 72
Cubic feet in one cubic meter	$35\frac{1}{3}$	35.32	1.5480 21
Cubic yards in one cubic meter		1.308	.1166
Cubic centimeters in one quart (U. S. Liquid)		946.3	2.9760 30
Cubic centimeters in one gallon (Imperial)		4542.	3.6572 50
Liters in one quart (U. S. Liquid)		.9463	$\bar{1}$.9760 30
Liters in one gallon (Imperial)	$4\frac{1}{2}$	4.542	.6572 50
Cubic inches in one liter		61.02	1.7854 72

MEASURES OF WEIGHT.

	APPROX. VALUE.	ACTUAL NUMBER.	LOGARITHM.
Grams in one pound (avoirdupois)		453.59	2.6566 66
Kilograms in one pound (avoirdupois)	$\frac{10}{22}$	.45359	$\bar{1}$.6566 66
Milligrams in one grain	65	64.799	1.8115 68
Grains in one gram	$15\frac{1}{2}$	15.432	1.1884 30
Ounces (avdp.) in one kilogram	$35\frac{1}{4}$	35.274	1.5474 55
Pounds (avdp.) in one kilogram	$2\frac{2}{10}$	2.2046	.3433 34
Short tons (2000 lbs.) in one metric ton (1000 kg.)	$1\frac{1}{10}$	1.1023	.0423 04
Long tons (2240 lbs.) in one metric ton (1000 kg.)	1	.9842	$\bar{1}$.9930 83
Metric tons (1000 kg.) in one short ton (2000 lbs.)	$\frac{9}{10}$	.90719	$\bar{1}$.9576 96

COMPOUND UNITS. (WORK AND PRESSURE.)

	APPROX. VALUE.	ACTUAL NUMBER.	LOGARITHM.
Kilogram-meters in one foot-pound		.13825	$\bar{1}$.1406 65
Foot-pounds in one kilogram-meter	$7\frac{1}{4}$	7.233	.8593 20
Kilograms per sq. cm. (pressure) in one lb. per sq. in.		.07031	$\bar{2}$.8470 14
Pounds per sq. inch in one kg. per sq. cm.	$14\frac{1}{4}$	14.223	1.1529 90

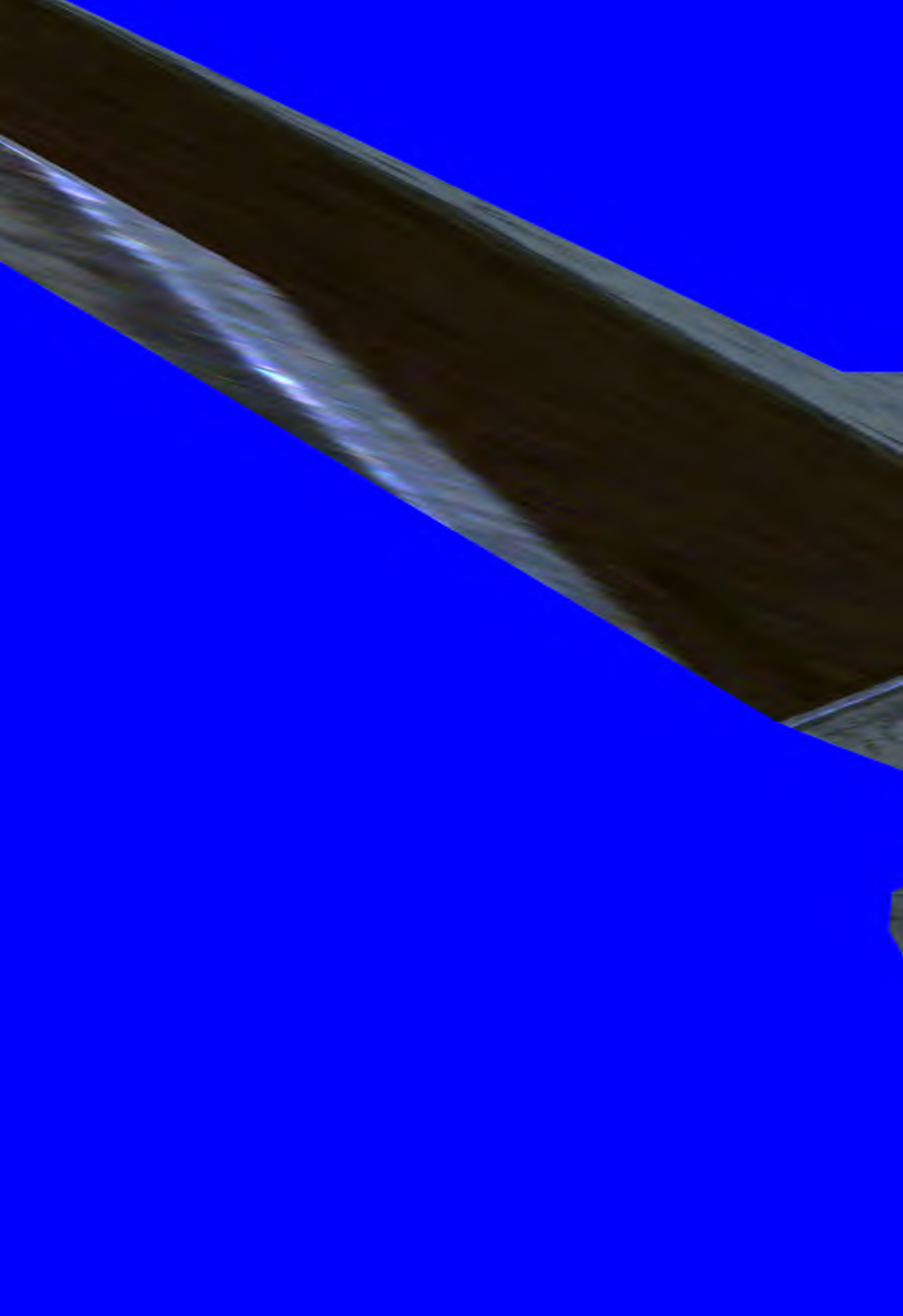
MEASURES OF HEAT.

These are given in connection with the subjects of the steam-engine and arc and incandescent lamps, where they naturally belong. The conversion of centigrade temperatures into Fahrenheit, or *vice versa*, has to be performed so often, however, that the data are given here. To convert centigrade degrees into Fahrenheit, multiply by $\frac{9}{5}$ or 1.8, and add 32. To convert Fahrenheit degrees into centigrade, subtract 32, and multiply by $\frac{5}{9}$; that is, —

$$t_f = \tfrac{9}{5}\, t_c + 32 \qquad \text{and} \qquad t_c = \tfrac{5}{9}\,(t_f - 32).$$

The values of the various units of heat are not always given exactly the same, for the reason that the original value obtained by Joule for the mechanical equivalent of heat was 772 foot-pounds for one pound of water heated one degree Fahrenheit. The later experiments of Rowland show that this should be about 780 foot-pounds,* depending upon the specific heat of water and the force of gravity.

* Everett's C. G. S. *System of Units*, 1891 Edit., pp. 99–101.



in accordance with standard specifications, deposits silver at the rate of one thousand one hundred and eighteen millionths (.001118) of a gram per second.

Third. The unit of electro-motive force shall be what is known as the international volt, which is the electro-motive force that, steadily applied to a conductor whose resistance is one international ohm, will produce a current of an international ampere, and is practically equivalent to one thousand fourteen hundred and thirty-fourths ($\frac{1000}{1434}$) of the electro-motive force between the poles or electrodes of the voltaic cell known as Clark's cell, at a temperature of fifteen degrees centigrade, and prepared in the manner described in the standard specifications.

Fourth. The unit of quantity shall be what is known as the international coulomb, which is the quantity of electricity transferred by a current of one international ampere in one second.

Fifth. The unit of capacity shall be what is known as the international farad, which is the capacity of a condenser charged to a potential of one international volt by one international coulomb of electricity.

Sixth. The unit of work shall be the Joule, which is equal to ten million units of work in the centimeter-gram-second system, and which is practically equivalent to the energy expended in one second by an international ampere in an international ohm.

Seventh. The unit of power shall be the Watt, which is equal to ten million units of power in the centimeter-gram-second system, and which is practically equivalent to the work done at the rate of one Joule per second.

Eighth. The unit of induction shall be the Henry, which is the induction in a circuit when the electro-motive force induced in this circuit is one international volt, while the inducing current varies at the rate of one ampere per second.

SEC. 2. That it shall be the duty of the National Academy of Sciences to prescribe and publish, as soon as possible after the passage of this Act, such specifications of details as shall be necessary for the practical application of the definitions of the ampere and volt hereinbefore given, and such specifications shall be the standard specifications herein mentioned.

Approved July 12, 1894.

The specifications prescribed by the National Academy of Sciences in accordance with the last section of the above act are as follows: —

SPECIFICATIONS FOR THE PRACTICAL APPLICATION OF THE DEFINITIONS OF THE AMPERE AND VOLT.

Specification A. — *The Ampere.*

IN employing the silver voltameter to measure currents of about one ampere, the following arrangements shall be adopted: —

The cathode on which the silver is to be deposited shall take the form of a platinum bowl not less than 10 centimeters in diameter, and from 4 to 5 centimeters in depth.

The anode shall be a disk or plate of pure silver some 30 square centimeters in area, and 2 or 3 millimeters in thickness.

This shall be supported horizontally in the liquid near the top of the solution by a silver rod riveted through its center. To prevent the disintegrated silver which is formed on the anode from falling upon the cathode, the anode shall be wrapped around with pure filter paper, secured at the back by suitable folding.

The liquid shall consist of a neutral solution of pure silver nitrate, containing about 15 parts by weight of the nitrate to 85 parts of water.

The resistance of the voltameter changes somewhat as the current passes. To prevent these changes having too great an effect on the current, some resistance besides that of the voltameter should be inserted in the circuit. The total metallic resistance of the circuit should not be less than 10 ohms.

Method of making a Measurement. — The platinum bowl is to be washed consecutively with nitric acid, distilled water, and absolute alcohol; it is then to be dried at 160° C., and left to cool in a desiccator. When thoroughly cool it is to be weighed carefully.

It is to be nearly filled with the solution, and connected to the rest of the circuit by being placed on a clean insulated copper support to which a binding-screw is attached.

The anode is then to be immersed in the solution so as to be well covered by it, and supported in that position; the connections to the rest of the circuit are then to be made.

Contact is to be made at the key, noting the time. The current is to be allowed to pass for not less than half an hour, and the time of breaking contact observed.

The solution is now to be removed from the bowl, and the deposit washed with distilled water, and left to soak for at least six hours. It is then to be rinsed successively with distilled water and absolute alcohol, and dried in a hot-air bath at a temperature of about 160° C. After cooling in a desiccator it is to be weighed again. The gain in mass gives the silver deposited.

To find the time-average of the current in amperes, this mass, expressed in grams, must be divided by the number of seconds during which the current has passed and by 0.001118.

In determining the constant of an instrument by this method, the current should be kept as nearly uniform as possible, and the readings of the instrument observed at frequent intervals of time. These observations give a curve from which the reading corresponding to the mean current (time-average of the current) can be found. The current, as calculated from the voltameter results, corresponds to this reading.

The current used in this experiment must be obtained from a battery, and not from a dynamo, especially when the instrument to be calibrated is an electro-dynamometer.

Specification B. — *The Volt.*

Definition and Properties of the Cell. — The cell has for its positive electrode, mercury, and for its negative electrode, amalgamated zinc; the electrolyte consists of a saturated solution of zinc sulphate and mercurous sulphate. The electro-motive force is 1.434 volts at 15° C.; and between 10° C. and 25° C., by

the increase of 1° C. in temperature, the electro-motive force decreases by 0.00115 of a volt.

1. *Preparation of the Mercury.* — To secure purity it should be first treated with acid in the usual manner, and subsequently distilled *in vacuo.*

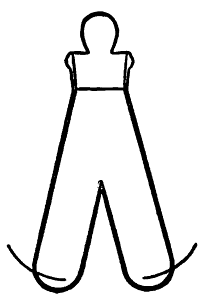
2. *Preparation of the Zinc Amalgam.* — The zinc designated in commerce as "commercially pure" can be used without further preparation. For the preparation of the amalgam one part by weight of zinc is to be added to nine (9) parts by weight of mercury, and both are to be heated in a porcelain dish at 100° C., with moderate stirring until the zinc has been fully dissolved in the mercury.

3. *Preparation of the Mercurous Sulphate.* — Take mercurous sulphate, purchased as pure, mix with it a small quantity of pure mercury, and wash the whole thoroughly with cold distilled water by agitation in a bottle; drain off the water, and repeat the process at least twice. After the last washing, drain off as much of the water as possible. (For further details of purification, see Note A.)

4. *Preparation of the Zinc Sulphate Solution.* — Prepare a neutral saturated solution of pure re-crystallized zinc sulphate, free from iron, by mixing distilled water with nearly twice its weight of crystals of pure zinc sulphate, and adding zinc oxide in the proportion of about 2 per cent by weight of the zinc sulphate crystals, to neutralize any free acid. The crystals should be dissolved with the aid of gentle heat, but the temperature to which the solution is raised must not exceed 30° C. Mercurous sulphate, treated as described in 3, shall be added in the proportion of about 12 per cent by weight of the zinc sulphate crystals, to neutralize the free zinc oxide remaining, and then the solution filtered, while still warm, into a stock bottle. Crystals should form as it cools.

5. *Preparation of the Mercurous Sulphate and Zinc Sulphate Paste.* — For making the paste, two or three parts by weight of mercurous sulphate are to be added to one by weight of mercury. If the sulphate be dry, it is to be mixed with a paste consisting of zinc sulphate crystals and a concentrated zinc sulphate solution, so that the whole constitutes a stiff mass, which is permeated throughout by zinc sulphate crystals and globules of mercury. If the sulphate, however, be moist, only zinc sulphate crystals are to be added; care must, however, be taken that these occur in excess, and are not dissolved after continued standing. The mercury must in this case also permeate the paste in little globules. It is advantageous to crush the zinc sulphate crystals before using, since the paste can then be better manipulated.

To set up the Cell. — The containing glass vessel, represented in the accompanying figure, shall consist of two limbs closed at bottom and joined above to a common neck fitted with a ground-glass stopper. The diameter of the limbs should be at least 2 centimeters, and their length at least 3 centimeters. The neck should be not less than 1.5 centimeter in diameter. At the bottom of each limb a platinum wire of about 0.4 millimeter diameter is sealed through the glass.



To set up the cell, place in one limb pure mercury, and in the other hot liquid amalgam, containing 90 parts

mercury and 10 parts zinc. The platinum wires at the bottom must be completely covered by the mercury and the amalgam respectively. On the mercury place a layer one centimeter thick of the zinc and mercurous sulphate paste described in 5. Both this paste and the zinc amalgam must then be covered with a layer of the neutral zinc sulphate crystals one centimeter thick. The whole vessel must then be filled with the saturated zinc sulphate solution, and the stopper inserted so that it shall just touch it, leaving, however, a small bubble to guard against breakage when the temperature rises.

Before finally inserting the glass stopper, it is to be brushed round its upper edge with a strong alcoholic solution of shellac, and pressed firmly in place. (For details of filling the cell, see Note B.)

NOTES TO THE SPECIFICATIONS.

(A) *The Mercurous Sulphate.* — The treatment of the mercurous sulphate has for its object the removal of any mercuric sulphate, which is often present as an impurity.

Mercuric sulphate decomposes in the presence of water into an acid and a basic sulphate. The latter is a yellow substance — turpeth mineral — practically insoluble in water; its presence, at any rate in moderate quantities, has no effect on the cell. If, however, it be formed, the acid sulphate is also formed. This is soluble in water, and the acid produced affects the electromotive force. The object of the washings is to dissolve and remove this acid sulphate, and for this purpose the three washings described in the specification will suffice in nearly all cases. If, however, much of the turpeth mineral be formed, it shows that there is a great deal of the acid sulphate present; and it will then be wiser to obtain a fresh sample of mercurous sulphate, rather than to try by repeated washings to get rid of all the acid.

The free mercury helps in the process of removing the acid; for the acid mercuric sulphate attacks it, forming mercurous sulphate.

Pure mercurous sulphate, when quite free from acid, shows on repeated washing a faint yellow tinge, which is due to the formation of a basic mercurous salt distinct from the turpeth mineral, or basic mercuric sulphate. The appearance of this primrose-yellow tint may be taken as an indication that all the acid has been removed; the washing may with advantage be continued until this tint appears.

(B) *Filling the Cell.* — After thoroughly cleaning and drying the glass vessel, place it in a hot-water bath. Then pass through the neck of the vessel a thin glass tube, reaching to the bottom, to serve for the introduction of the amalgam. This tube should be as large as the glass vessel will admit. It serves to protect the upper part of the cell from being soiled with the amalgam. To fill in the amalgam, a clean dropping-tube about 10 centimeters long, drawn out to a fine point, should be used. Its lower end is brought under the surface of the amalgam, heated in a porcelain dish, and some of the amalgam is drawn into the tube by means of the rubber bulb. The point is then quickly cleaned of dross with filter paper, and is passed through the wider tube to the bottom, and emptied by pressing the bulb. The point of the tube must be so fine that the amalgam will come out only on squeezing the bulb. This process is repeated

until the limb contains the desired quantity of the amalgam. The vessel is then removed from the water-bath. After cooling, the amalgam must adhere to the glass, and must show a clean surface with a metallic luster.

For insertion of the mercury, a dropping-tube with a long stem will be found convenient. The paste may be poured in through a wide tube reaching nearly down to the mercury, and having a funnel-shaped top. If the paste does not move down freely, it may be pushed down with a small glass rod. The paste and the amalgam are then both covered with the zinc sulphate crystals before the concentrated zinc sulphate solution is poured in. This should be added through a small funnel, so as to leave the neck of the vessel clean and dry.

For convenience and security in handling, the cell may be mounted in a suitable case, so as to be at all times open to inspection.

In using the cell, sudden variations of temperature should, as far as possible, be avoided, since the changes in electro-motive force lag behind those of temperature.

Respectfully submitted.

HENRY A. ROWLAND,
Chairman.
HENRY L. ABBOT,
GEORGE F. BARKER,
CHARLES S. HASTINGS,
ALBERT A. MICHELSON,
JOHN TROWBRIDGE,
CARL BARUS,
} *Committee.*

At a meeting of the National Academy of Sciences, held in New York Feb. 9, 1895, the above report was accepted and unanimously adopted by the Academy.

At the same meeting it was voted by the National Academy of Sciences to prescribe and to publish the specifications of details necessary for the practical application of the definitions of the ampere and volt, as required by the law of July 12, 1894.

O. C. MARSH,
President of the National Academy of Sciences.
ASAPH HALL,
Home Secretary.

MAGNETIC UNITS.

These are given in the beginning of the chapter on "Principles and Construction of the Dynamo," where they may be more conveniently and concretely considered.

Miscellaneous Units, Standards, and Terms employed in the various branches of the subject are defined or explained as far as possible where they occur.

CHAPTER IV.

CLASSIFICATION AND SELECTION OF ELECTRIC-LIGHTING SYSTEMS.

ELECTRIC-LIGHTING classification, like that of almost any subject, is more or less arbitrary, and is adopted merely for convenience. Considered in this light, classification is a great help; but we should carefully avoid the common mistake of forcing it too far by attempting to make the facts fit the classification, instead of the classification fitting the facts.

Electric-lighting apparatus may be classified with reference to various considerations. For example, it may be classified with reference to the system as a whole, or with reference to some of its most important elements or characteristics.

Central Stations and Isolated Plants. — Considered as a whole, electric-lighting systems may be divided into two important classes, — central stations and isolated plants. These two classes sometimes merge into each other, and peculiar cases might occur which would be on the dividing line; but ordinarily the distinction between the two is radical, and introduces considerable differences in design, construction, and operation. In fact, these two types of plant must be considered as quite different problems in electrical engineering, and usually there is no difficulty in distinguishing between them. A central station electric-lighting system is usually extensive and elaborate technically, and quite complicated and difficult in its business management. It consists of a large and complete collection of machinery for generating and controlling the electric current. This generating-plant is usually contained in one or more buildings entirely devoted to it, and probably specially built for it. The central station is usually owned and operated by a company having no other business. From the central station a large number of electrical conductors run out in every direction. These conductors supply electric current to feed lamps for many different purposes, and for the use of many different and independent customers; and a separate

measurement or estimate of current and charge therefor is made in the case of each customer.

Isolated electric-lighting plants, on the other hand, are comparatively small and simple in construction and management. They are usually entirely local; that is, the plant supplies current for lighting a single building or group of buildings. The generating plant or machinery is ordinarily located in the cellar, or some small portion of the building. An isolated plant usually supplies current only to its owner or his tenants, and is owned and operated by a private individual, company, or institution, and constitutes only a small and incidental part of its affairs. Light is supplied to the various buildings, or parts of the building, usually without attempting to make separate measurements or charges, which eliminates the somewhat troublesome element of meters, and greatly simplifies the business management.

Incandescent and Arc Lighting. — Electric lighting may also be classified with reference to the *lamps;* that is, we have incandescent-lighting and arc-lighting systems. A few years ago it could have been said that incandescent systems were operated at constant potential, that is, constant voltage, the lamps being connected to the circuit in parallel; and it could have been said that arc systems were almost invariably supplied with a constant current, that is, one having a fixed number of amperes, the lamps being arranged in series. This distinction still holds good to a certain extent; but quite recently there has been an extensive introduction of arc lamps on incandescent circuits with constant potential current. These lamps possess the advantage over the ordinary constant-current lamps that the current is of low potential; that is, only about one or two hundred volts instead of two to five thousand volts which are usually employed on constant-current arc circuits. On the other hand incandescent lamps are sometimes operated on the constant-current circuit, being called series-incandescent lamps; but these are not very common, and the use of them does not seem to increase to any very great extent.

The advantages of incandescent electric lighting are: —

The fact that lamps of any desired size from one candle-power to several hundred can be obtained and easily substituted one for the other. The light is steady and agreeable in quality, being in

those respects better than a very good gas light. It is practically free from danger of setting fire even to the most inflammable material. The lamps can be put in almost any place or position. The wires required to feed an incandescent lamp are small, and can be easily placed in fixtures, mouldings, etc., and thus concealed.

The arc light, on the other hand, has the advantage of being simpler and cheaper to install, particularly in regard to wiring; and it gives more light for a given amount of electrical energy than an incandescent lamp. The ordinary arc lamp consumes 10 amperes and 45 volts, which is 450 watts; and it gives about 350 candle-power (i.e., mean spherical). This is at the rate of about 1.3 watts per candle-power. The ordinary incandescent lamp requires 110 volts and .5 ampere, which is 55 watts, and gives 16 candle-power. This is at the rate of about 3.5 watts per candle-power. Therefore the arc lamp gives nearly three times as much light for the same amount of electric power. To offset this advantage, however, the arc lamp is quite limited in the range of its candle-power; that is to say, to obtain good results, an arc lamp requires a minimum of about 40 volts and 8 amperes, which gives about 300 candle-power. If it is attempted to make an arc lamp very much smaller than this in power, it is apt to be unsteady and liable to go out entirely; but considerable progress is now being made with small arc lamps. It is possible to make arc lamps of greater candle-power than the ordinary, to almost any extent, even as high as several hundred thousand candle-power; but such lamps are only used for special purposes, such as search lights. Hence the arc lamp is not suited to places where small amounts of light are required, or where a uniform distribution of light is wanted.

In some cases arc lamps have been arranged to throw all their light upward against a whitened ceiling. In this way the direct light of the arc is not visible, and the indirect illumination obtained is much softer and more distributed. This plan has been quite successful in several places, and makes the arc lamp applicable in many places in which the incandescent lamp would ordinarily be employed.

The arc light is often objectionable because its great intensity and the glaring quality of its light are disagreeable, or even

actually injurious, to the eye, unless it is shaded by porcelain or ground glass, which absorbs about half the light, and sacrifices a large part of the power and economy. The color of the light, however, is almost pure white, and closely resembles sunlight in its quality, and is, therefore, sometimes desirable in shops, factories, etc., where colors are to be brought out in their true relations, or photographic operations are carried on. In a general way it can be said that incandescent lamps are suited to interior lighting and to comparatively small spaces, whereas arc lamps are adapted to outdoor lighting or to large spaces, such as railway stations, etc.

The arc light is often used for temporary illumination where work is being done in excavations, buildings, etc., at night. Its advantages in these cases are its great power, and the simplicity of wiring needed. The engines and dynamos employed for arc lighting do not require to regulate so perfectly as for incandescent lighting; and this is also an advantage for temporary installations, since it avoids the necessity for very fine machinery, or careful setting and adjustment of the same.

Alternating and Direct Currents. — The third classification of electric-lighting systems is in respect to *current;* and we have direct-current and alternating-current systems, the direct current being one which flows in one direction only, and the alternating being a rapidly reversed current. The following table shows the various forms of direct and alternating current systems which are employed.

DIRECT CURRENT.	Dynamos alone.
	Dynamos and auxiliary secondary battery.
	Dynamos and dynamotors.
	Primary batteries.
ALTERNATING CURRENT.	Dynamos alone.
	Dynamos and transformers.
	Dynamos and "step-up" and "step-down" transformers.

The general advantages of the direct-current system are: —

The potential or voltage is low. This applies, however, to incandescent and constant potential arc lamps, and not to constant current arc lamps. The direct current also possesses the advantage that motors of any desired size can be connected to the circuit and operated very satisfactorily. Direct currents are

also suited to electroplating or other electrometallurgical or electrochemical purposes, and storage batteries can be used with them. Direct currents are also largely free from peculiar actions and losses due to self-induction and electrostatic capacity, which may occur in the case of alternating currents. The great advantage of the alternating current is due to the fact that it can be generated at a high potential, usually 1000 or 2000 volts, and transmitted a considerable distance over a comparatively small wire without serious loss. This economy in the size of wire required is due to the fact that, since the potential in volts is high, the current in amperes, and therefore the cross-section of the wire needed, are small. When a point where lights are to be run is reached, the voltage is brought down by means of transformers to, say, 50 or 100 volts, and wires may be run about a house, for example, and carry this low-tension current, which has thus been made harmless. This ability to transform the alternating current from one voltage to another, as desired, by means of simple induction coils having no moving parts, is the great advantage to which the alternating current almost entirely owes its importance. The alternating current also has the advantage of requiring no commutator on the dynamo which generates it, two simple collecting rings being sufficient; but a separate machine or winding is required to furnish a direct current to excite the field magnet, and this involves a commutator.

The alternating current can also be regulated by means of the counter electromotive force of a "choke coil," which shuts off the current without wasting so much energy as the simple resistance coils used to control direct currents. Storage batteries cannot, however, be used with the alternating current. The relative merits and economy of the direct and alternating current systems have given rise to more discussion than any other subject in electrical engineering; and the question is still an unsettled one, even the most competent authorities not being agreed upon the matter. This problem involves a great many fine points, and would depend upon the conditions in each particular case. It is discussed more fully later in its bearing upon the problem of selecting a system in a given case. In this connection it is one of the most important questions which an electrical engineer is called upon to decide.

High and Low Potential. — The fourth and last classification of electric-lighting systems is with reference to the use of "high-tension" and "low-tension" currents. The term tension, however, is old-fashioned, and was formerly employed to designate what we now call potential or voltage. It is impossible to exactly define what constitutes a high-tension system, since much depends upon the circumstances and the point of view. If we look upon the question in its relation to fire risk or insurance, we find that anything over 250 volts is called a "high-tension" system, and is covered by a different set of rules.*

If we view the matter as electrical engineers, where many other elements beside fire risk have to be considered, we find that the National Electric Light Association has defined a high-tension system to be one using 350 volts or more.† The reason for this higher limit is possibly the fact that anything under 350 volts is almost perfectly safe, so far as danger to persons is concerned; and the problem of insulating and controlling electric currents under 350 volts is not difficult from the engineering standpoint, and various constructions are allowable which would not be proper for high-tension systems of 1,000 volts, for example. If we consider the question solely from the point of view of personal danger, that is, liability to fatal accident, then we can probably place the limit at 500 volts, because thousands of miles of circuits carrying currents of 500 to 600 volts are in use in this country for operating electric railways; and the records show that there have been very few fatal accidents produced by the *current* from these circuits.

Thus we see that there are several different definitions of high and low tension systems according to circumstances, and each may be perfectly correct from a certain point of view. In electric lighting there is usually no difficulty in distinguishing high and low tension systems, since practically the only currents now used in this country are the alternating current of 1,000 to 2,500 volts, the arc system of 2,000 to 5,000 volts, or the direct current incandescent (and arc) circuits of 110, 220, or at most, 250 volts. The five-wire system sometimes adopted in Europe and operated at

* National Board of Fire Underwriters' Rules. See *Electric Lighting Specifications*, Merrill, p. 153.

† *Rules*, Nat. Elec. Assoc., adopted at Washington, Feb., 1894.

about 440 volts would usually be called high-tension, and so would most series incandescent systems.

The Selection of a System. — The classification given in the preceding pages may be tabulated in the following form, from which the choice of an electric-lighting system must be made: —

CLASSES.	SYSTEMS.
CENTRAL STATIONS.	1. Incandescent. / Arc.
ISOLATED PLANTS.	2. Direct. / Alternating.
	3. High-tension. / Low-tension.

The actual selection of a certain system and type of apparatus for a particular case depends, of course, largely upon the peculiar circumstances that may exist, and the greatest care should be exercised in taking into consideration the local conditions which, rather than general principles, usually determine the success or failure of an electric-lighting plant. The safest guide is, of course, *experience*; and the engineer, if he does not himself possess the experience, should, if possible, find some case where the conditions resemble those with which he has to deal. By a careful study of the results obtained in the case selected as an example, one can often get the benefit of much experience which will save time and trouble, eliminate mistakes, and secure results that would not otherwise be possible.

It is foolish for an engineer to launch out without regard to the experience obtained by others at great cost in similar cases, on account of conceit or false pride, which makes him unwilling to profit by results already obtained. Many a partial or total failure would have been prevented by a little more carefulness and common-sense in this direction. It is almost always a mistake for an engineer to employ some untried method or apparatus solely upon his own knowledge and responsibility, unless it is absolutely necessary, or unless those who have to pay for the experiment understand the facts of the case; and when the engineer goes so far as to try his own inventions (in regard to which he is, of course, prejudiced), at the expense of others, it is positively dishonest. A certain amount of experiment and novelty is a necessary element of each engineering problem, and this con-

tributes to general improvement and progress; but experiments should usually be tried as such, and all persons interested should realize that one is being tried: in fact, the proper place for engineering experiments is in the experimental department of some company or institution. Nothing is more important or interesting than experiment, and the world would stand still without it; but in practical and regular work it is usually found that the simplest, most standard, and well-tried devices give by far the most satisfactory results. Radical and sensational departures from established practice are usually the cause of regret to all concerned.

The Size of Plant. — This the engineer must definitely know before making any exact plans or calculations. It is usually ascertained in terms of the number and distances of lamps that will be required, by making a thorough canvass of the city or town, or that portion of it which it is intended to light. The probable number of lamps which the station will supply when it first starts up, and what the number is likely to become afterward, are matters upon which the entire design and construction of the station depend.

Let us consider the simplest case first, and assume that the plant to be installed is an isolated one for lighting one building or group of buildings. In this case there is little or no uncertainty; and the low-tension, direct-current, constant-potential system would naturally be selected. Since the distances and lengths of wire required would be small, there would be no reason for using a high-tension system of any sort. During the last few years the utility and scope of this system have been greatly extended by the fact that many forms of arc lamp have been devised which work admirably upon constant-potential circuits, being, if anything, better than constant-current arc lamps. These are run, two in series, on the ordinary 110-volt circuit, with a small amount of resistance in series with them.

This possibility of running both arc and incandescent lamps on the same circuit avoids the necessity of putting in special constant-current machines to run the arc lamps, which was formerly done even in the case of isolated plants, and involved considerable extra first cost and much more trouble in running the plant. Arc lamps operated in this way on a low-tension cir-

cuit are limited in regard to distance from the generator, just as in the case of low-tension incandescent lamps; but it has occurred to the author that since a certain amount of resistance is needed in series with constant-potential arc lamps, it would be perfectly possible to use the wires leading to the lamp for that resistance, thereby avoiding the necessity of a special resistance in the lamp, and at the same time permitting the lamp to be placed at a considerable distance from the generator.

The possibility of using other systems for isolated plants is rarely considered, but is by no means out of the question. It would be perfectly feasible to operate a low-tension incandescent system by means of an alternating-current dynamo generating, say, 110 volts. Of course no transformers would be required in this case, and there would be the apparent advantage of avoiding the commutator of a direct-current dynamo; but the commutator of the exciter is fully as objectionable: in fact, there would be two machines to take care of instead of one. Several plants installed by J. E. H. Gordon and others for incandescent lighting were operated by low-tension alternating currents. But those early systems were rather crude; and since the direct-current system of incandescent lighting was perfected by Edison, low-tension alternating systems have been rarely used in electric lighting. The objection to these systems, besides the one already stated, is the fact that up to the present time it has not been possible to operate motors very satisfactorily with the simple alternating current; and that would be a fatal objection for isolated plants in which motors are used, particularly in this country. In short, the low-tension direct current is very satisfactory for ordinary isolated plants, since arc and incandescent lamps, motors, dynamotors, electric heating and electrometallurgical apparatus, and storage batteries can all be operated perfectly in connection with it.

Central Stations. — When isolated plants become very large, as, for example, in the case of a number of factories or other buildings scattered along some distance apart, it then becomes practically the same question as selecting a system for a central station, there being, as already stated in the beginning of this chapter, no absolute dividing line between the two. The selection of the best system for a central station is the most serious problem that

the electrical engineer is called upon to solve, and having once decided, it is almost impossible to change. If the business of the station is to be confined to arc lighting for streets, the regular constant-current arc system would naturally be adopted. There are a number of stations of this kind in this country, the business of which is entirely, or largely, arc lighting. In such a case there would formerly have been little question, but Fifth Avenue in New York City is now lighted by arc lamps on the low-tension (230 volt, 3 wire) system; and the alternating-current system is being used in St. Louis and other cities for supplying arc lamps by means of transformers, the primary circuits of which are connected in parallel as usual, but the secondaries give a constant current. The Westinghouse Company also have a series system for supplying alternating-current arc lamps, which are placed on the main circuit without transformers.

If the average distances of the lamps from the station are not very great, the low-tension direct-current system is very satisfactory for arc lamps, particularly if incandescent lamps are also supplied. But a large station usually does a general business, including arc and incandescent lighting and power distribution to various distances from the station; and the problem then becomes very complicated.

Alternating vs. Direct Current. — This brings us face to face with the much-discussed question of high-tension alternating *versus* low-tension direct current, concerning which there are radical differences of opinion among the best authorities. In both America and Europe, the greater number of incandescent lamps are now operated by the low-tension direct-current system; hence custom sanctions its use. But allowance should be made for the fact that the alternating current has not been so long in general use. The only reason for adopting high-voltage alternating or other currents in electric lighting is to reduce the cost of the conductors required. The cross-section of wire needed to convey a given amount of electrical energy in watts, with a given percentage of "drop," or loss of potential in volts, is inversely proportional to the square of the *E.M.F.* employed. In other words, it only requires a wire of one-quarter of the cross-section and weight, if the voltage be made twice as great; hence the great economy in conductors secured by the use of high-tension currents.

This advantage can be realized either in saving the weight of wire required, or in transmitting the current to a great distance with the same weight of copper.

In comparing and deciding between the alternating- and the direct-current systems, there is a tendency to think only of the cost of the copper conductors, and to forget the cost of transformers, greater complication, and positive danger to human life, all of which ought to be counted against the high-tension alternating system. Furthermore, an electric-light plant usually runs a large part of the time lightly loaded; and during all that time the alternating system is much more wasteful of energy than the direct; because in the former case the leakage current is always flowing in the transformers, whereas, in a direct-current system the loss of energy in the distribution system is extremely small at light load, since it varies as the square of the current. If the distances of the lamps are very great, — several miles, for example, — then, however, there is little or no question, and an alternating-current system with transformers would almost necessarily be adopted. Formerly, in this country, the potential was almost always 1,000 volts; but now 2,000 volts, or even more, are frequently used, which still further extends the distance at which lamps can be economically operated. By the use of potentials of 10,000 to 20,000 volts, obtained by "step-up" transformers, or directly from the alternator, the possible distance may become 20 to 50 miles, or even more. If, on the other hand, the population is fairly large and dense, so that a sufficient number of customers can be found within about 1½ mile of the station, then, for the reasons stated above, a low-tension direct system is usually more satisfactory.

The limit of distance at which the alternating system is preferable to the direct cannot be fixed exactly, since it depends upon so many factors, one of which, for example, is *the value of human life*. Prof. J. A. Fleming states that the economical limits are reached in the two-wire direct-current system (about 110 volts) "when the mean length of the feeders is some 300 or 400 yards;" and in the three-wire system (about 220 volts) "when the mean length of the feeders is from half to three-quarters of a mile" (*The Alternating Current Transformer*, vol. ii., p. 337). With a mean length of feeder of ¾ mile, lamps can be fed at a distance

of 1½ mile from the station, which makes it possible to supply a circular district three miles in diameter, if the station is at the center; if it is not at the center, the available district will be correspondingly smaller. Other parts of the city can be lighted by other central stations, or by sub-stations. It is also possible by certain methods to considerably extend the economical limit of distance. One plan is to generate a higher electrical pressure at the station, to supply those lamps which are remote; that is, the feeders running to the most distant parts of the district are operated at a higher voltage than the others. This higher pressure is produced by special dynamos, or, more conveniently, by small auxiliary dynamos, called "boosters," which raise the voltage in certain feeders. Methods of this sort have been very successfully applied by the Edison Electric Illuminating Company of Brooklyn, and in other places; and in this way lamps are operated at a distance of two or three miles from the station.

The low-pressure direct-current system should generally be selected for any case in which the station can be located in or near the district to be lighted. In support of this statement we may refer to the fact that the stock of the companies operating low-pressure systems in New York, Brooklyn, Boston, Chicago, and Philadelphia was quoted on April 15, 1893, at prices which averaged about 150, the lowest being 110, and the highest 220. Even during the extraordinary financial depression in July, 1893, these stocks did not fall any more than the best railroad securities. These are considerably higher than the stock of corresponding companies employing the high-pressure alternating or arc systems; and this is a much more positive proof of the success of the low-pressure systems than any abstract argument. Similar statements apply to European stations also.

If the station must be located at a distance of several miles from the district to be lighted, as, for example, when a water-power is to be utilized, then it is practically necessary to adopt the high-pressure alternating system; and many fine stations of this kind exist throughout America and Europe. The alternating system would also be more economical and suitable where the houses of a town are very much scattered or stretched out in a long line, or where two or more neighboring towns are to be lighted from one station.

CHAPTER V.

THE LOCATION AND GENERAL ARRANGEMENT OF ELECTRIC-LIGHTING PLANTS.

To determine the location of an electric-lighting plant is often a matter of great difficulty, owing to the fact that so many considerations are involved, the most prominent of which are the following: —

1. Kind of power used (water or steam).
2. State and municipal laws and insurance rates.
3. Size, form, and character of the district and distribution of lamps to be lighted.
4. Cost of ground space.
5. Room for extension.
6. Convenience of coal supply.
7. Convenience of water supply for boilers and condensers.
8. Possibility of obtaining good foundations.
9. Possibility of obtaining good chimney draught.

The kind of power adopted may absolutely determine the location of a plant, when, for example, a certain water power is to be employed that is only available at a certain point. In fact, if a water power of proper amount, reliability, and proximity exists, it would naturally be used wherever electric lighting is required, and the generating-plant would be put close to it.

If steam power be adopted, the location of the plant is not so limited; but even in that case it is necessary to carefully consider question of coal and water supply, which will be discussed under those headings.

State and municipal laws and insurance rules might in some cases determine or affect the location of the station. For example, if a high-tension current were forbidden by law, then it would be necessary to locate the station in or near the district to be lighted. On the other hand, if it were not permissible to locate a station in a city on account of objection to smoke or vibration, then the station would have to be put outside of the

city limits, and a high-tension transformer system employed. These matters depend entirely upon local law and custom, and no general rules can be laid down. Ordinarily, however, it is allowable to locate a station within the city if it be desirable to do so. But it is well to choose a site surrounded by factories, stables, etc., the owners or occupants of which are not likely to claim damages for smoke or vibration nuisance. A station situated among fine residences, for example, would almost certainly have serious trouble on this account, and a little discretion in this matter might save much annoyance and litigation.

The size, form, and character of the district to be lighted is to be determined by general circumstances, verified by a careful study and canvass to ascertain as definitely as possible the location and number of lights likely to be required, and the purposes for which they are to be used.

It is well to make an accurate map or plan showing these facts, which would be useful, not only in locating the station, but also in determining the amount of apparatus, conductors, etc., required ; also in making financial calculations. The purpose for which lamps are used is important, since it indicates when and for how long they will be lighted. For example, butcher and dry-goods shops usually close early in the evening, whereas restaurants and saloons are open late. Professor E. P. Roberts has gone into this matter in detail, and tabulated what may be expected of different kinds of customers.* By adding up in this way the total number of lights that will probably be burning each hour of the day and night, it is possible to predetermine the load diagram or curve showing the current used at each hour, which would be of the greatest value in designing the plant. A certain amount of selection can be made in regard to the location and business of the customers, in order to improve the form of the district or the load diagram ; but, of course, a company usually takes all the business that is obtainable, particularly in the beginning.

Mr. Hordern, in London *Lightning* of April 14, 1894, gives diagrams for the different classes of customers of the Westminster station, which show, however, that in practice it is very difficult to forecast a new customer's bill.

* "The Design of a Central Station for Incandescent Lights." *Electrical World*, N.Y., March 25 and April 22, 1893.

Having ascertained or estimated the number and distribution of the lamps, and, therefore, the size and form of the district, the next step would naturally be the determination of the exact location of the station.

This order of procedure might, however, be reversed, as the location of the station may be fixed by certain local circumstances, and then the size and form of the district to be lighted would be determined by the position of the station. In either case the ideal arrangement would, of course, be that in which the district was a perfect circle, with the station located at the center. Theoretically, the station should be located at what might be called the center of gravity of the system, determined by giving each part of the district a value proportional to the number of lamps to be supplied. This could be applied to any district, however irregular in form; but this ideal position would rarely be realized in practice, and a slight or even considerable departure from it would not be objectionable. Low-tension systems, however, that is, incandescent lighting systems employing 100 to 250 volts, usually require the station to be placed somewhere near the center. Exceptions to this rule may be made for special reasons, and by the use of peculiar devices. For example, the system may be operated with a larger percentage of loss of potential on the conductors than is usually allowed, or part of the dynamos can be run at a higher voltage than the others, in order to supply lamps at a greater distance, or the current in certain of the feeders may be raised in voltage by auxiliary dynamos, commonly called "boosters." By such means low-tension systems are successfully operated where the station is located at a considerable distance from the center of the district, or even entirely outside of it.

In the case of high-tension systems the station can be located at some distance from the district to be lighted, even several miles away. In fact, the sole reason for employing high potentials for electric lighting is the fact that a given amount of electrical energy can be conveyed by much smaller wires if high-voltage currents be used. In fact, with a given amount of electrical power in watts and a given *percentage* of loss in volts, the cross-section of conductor required is inversely proportional to the square of the number of volts. This ability to carry electrical energy over comparatively small wires to considerable distances

permits the station to be located in almost any desired position, irrespective of the size, shape, and position of the lighting district, within reasonable limits. This applies to alternating incandescent lighting and to series arc lighting, or to any other system using currents of 1,000 volts or more. The advantage of being able to locate the station wherever it may be convenient to have it, is offset by two serious facts, as already stated.

First, the danger of killing persons and animals by contact with wires carrying high-voltage currents.

Second, the difficulty of insulating high-voltage currents. This serious question between high and low tension systems has been long, and somewhat fiercely, discussed by electrical engineers; but there is probably no general answer, and each system has its proper sphere of usefulness, depending upon circumstances. The various methods of electrical distribution which will be discussed in Volume II., are paramount in determining the location of the generating-plant and the choice of an electric-lighting system.

The cost of ground space required is in many cases a controlling condition. It may happen that the rent or cost of sufficient ground space may be so high as to absolutely preclude the placing of the station in or even near the district to be lighted. This would oblige the station to be put some distance away, where ground would be sufficiently cheap, in which case a high-tension system would almost necessarily have to be adopted. This shows how the various parts of this problem are interdependent, and a change in one may affect the others.

A high value of real estate would also affect the arrangement of the station, giving rise to three or four essentially different types of station, depending upon the cost of the ground space. These arrangements of station will be considered on page 46. In most cases the cost of ground space and its effect upon the location of the station are quite definite and easily ascertained.

Room for extension should always be provided, because it has been the history of nearly all successful stations and plants that their business has rapidly and greatly increased, it being not uncommon for the number of lights to double each year for several years. Provision should, therefore, be made to enable the plant to be enlarged to at least twice, and perhaps four or six times, its original size. All the land need not be obtained in

the first place, provided it can surely be had at a reasonable price when required.

The convenience of coal supply should be carefully considered in locating electric-lighting plants, if steam-power is to be used. If possible, a site should be selected directly upon some railway, or sufficiently near to be connected by a branch track or siding; or directly upon the water front, so that coal vessels can be brought alongside, and in either of these cases the arrangement should be such that the coal can be directly unloaded from the cars or vessels into the bins from which the boilers are supplied. Rehandling of the coal should be avoided as far as possible; and if the coal can be made to move or discharge itself by gravity, so much the better. If, however, it is not possible to place the plant where coal can be obtained directly from railway or boat, then it should be located so that the carting or other handling of the coal involves the minimum trouble and expense. The possibility of the coal supply being temporarily cut off by severe snow-storms, floods, or strikes should also be considered in locating and arranging the plant.

Convenience of water supply should also be given careful attention. In cities the supply may usually be obtained from the city waterworks, in which case it may not be considered in locating the station. This would usually involve, however, a heavy water tax, and it might therefore pay, even in that case, to sink an artesian or other well, or obtain water from some other source. In small towns regular waterworks do not ordinarily exist, and the plant would have to depend upon wells or some other natural supply of water, such as a stream, pond, or lake. In the case of natural water supply the location of the plant would have to be made accordingly.

The water supply required in electric lighting may be of two kinds: First, that needed for the boilers; and second, water for condensation, if condensing engines be used. The first kind of water should be very pure, if possible, to avoid the deposition of scale and sediment in the boilers, which is most objectionable. The water for condensing need not, necessarily, be very pure either mechanically or chemically, if surface condensers are employed; in fact, salt water can be used, as in the case of marine engines. But even in condensers it is desirable to have

reasonably pure water, and therefore it is generally found expedient to secure an ample supply of good water for both purposes; or, to put it another way, it would not pay to use condensing engines unless a good and sufficient supply of condensing water can be relied upon. Water supply for boilers and condensers is discussed in Chapter IX.

The possibility of obtaining good foundations is too serious a matter to be neglected in locating electric-light plants, because the machinery used is very heavy, and it should be substantially and firmly placed, in order to work steadily and properly. A careful investigation of the character of the ground should be made, to be sure of having solid foundations, as it might happen that the existence of soft ground or quicksand would involve great trouble and expense.

The matter of transmitting vibrations from machinery to adjacent buildings should be carefully considered, as it may be the cause of great annoyance, or even actual damage. This question is discussed in the next chapter, under the head of "Foundations."

The obtaining of a good draught for the boiler fires is another matter which must not be ignored in locating and arranging a plant. If natural draught by means of a chimney be adopted, two questions are involved: First, the foundations for a sufficiently high chimney must be particularly good, and even better than those for the building or machinery, because the slightest settling will throw the stack out of plumb, the effect being magnified by the height of the chimney; secondly, the formation of the land in the neighborhood of a chimney very considerably affects the draught. For example, if a chimney were located near a line of hills, and the prevailing winds happened to be from the hills toward the chimney, the effect would be to cause the wind to be deflected downward upon the chimney, which would tend to oppose the draught. In a case of this kind, or wherever natural draught is not to be obtained, it would be necessary to resort to mechanical draught of some kind.

Thus it will be seen that there are numerous important factors involved in determining the location of a station; and it is usually a great mistake to overlook any of them, or, on the other hand, to give undue weight to any particular one.

Location of Generating-Stations at Coal-Mines. — The possibility of locating large electrical generating-stations directly at coal-mines, and transmitting the energy by wires to the large cities for light, power, etc., has been proposed and discussed.*

This is the extreme case of the location of a central station entirely with reference to coal supply. It is largely a question of whether it costs more to carry the coal or the electrical energy to the given point. The plan would have the enormous advantage of eliminating the serious evils due to excessive smoke in large cities, as well as the trouble and dirt involved in handling coal and ashes. Advanced civilization will probably demand it in the future; but railways and other established interests would combat it, and it is doubtful if the times are quite ripe for attempting it, except in places where the conditions are particularly favorable. A compromise scheme has been proposed by the author † in which the station would be located at a sufficient distance from the city to avoid the nuisance of smoke and dirt, and also reduce the handling of the coal. For example, a large station located in New Jersey could supply New York City, and would secure great saving in cost of land, coal, labor, etc.

ARRANGEMENT OF AN ELECTRIC-LIGHTING PLANT.

The general arrangement of an electric-lighting plant or station demands the greatest care and forethought. It depends chiefly

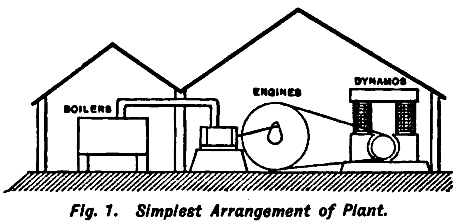


Fig. 1. Simplest Arrangement of Plant.

upon two facts, — its location and the kind of machinery adopted. The location of the station, particularly with reference to the value of real estate, gives rise to several radically different arrangements. If the cost of ground-space is low, and there is ample

* "Generating Power at Coal Fields and Transmitting it Electrically to Industrial Centres," *Elec. World*, Dec. 31, 1892. "The Utilization of Coal Mines." Professor Blake. *Sci. Amer. Sup.*, July 8, 1893.

† "Coalless Cities," *Cassier's Mag.*, December, 1895.

room, the simplest, and usually the best, arrangement is that shown in Fig. 1, in which the boilers, engines, and dynamos are all placed on the ground, the relative position being such that the steam flows directly from the boilers to the engines with a minimum length of pipe. This arrangement is natural and desirable in every way.

If, however, the cost of sufficient ground-space is too great to allow this plan to be followed, then it obviously becomes necessary to place some of the apparatus above the rest; that is, we must have a building with two or more stories.

In the first large electric-lighting central station built in the world — the Pearl-street Station of the Edison Electric Illuminating Company of New York, which began running in 1882 — this problem was solved by placing the boilers on the ground, the engines and dynamos, which were direct-coupled, being located on the floor above, which consisted of iron beams supported on iron columns. This arrangement was a natural one, but was not found to work very satisfactorily, and is probably radically wrong, for the reason that the tendency of steam-engines to vibrate because of their reciprocating motion makes it practically imperative to place an engine of any size upon a solid foundation directly upon the ground.

Boilers, on the other hand, although heavy, do not tend to cause vibration, and simply require a sufficiently strong support to carry the dead weight. The arrangement adopted, therefore, in several of the later Edison stations has been to place the boilers upon the second or even third story, and locate the engines on the ground floor, and the dynamos either on the ground floor or on the floor above, being connected by belts to the engines. This latter arrangement is not altogether satisfactory, because it requires vertical belts, which rarely work well, it being a fact that belts require a considerable horizontal distance between the centers of the pulleys in order to run properly. A better arrangement is to have the engines and dynamos both on the ground, and directly coupled, or connected by belt.

Several arrangements of belting and shafting are commonly used in which vertical belts are avoided, although the dynamos are placed on the floor above the engine, thus saving ground-space. The arrangement in Fig. 2 requires a considerable amount

of the floor to be cut away, in order to allow the belt to pass diagonally through it. The arrangement in Fig. 3 is intended to avoid this difficulty by running the belt parallel with the floor, at a sufficient distance above it to allow persons to walk underneath. In Fig. 4 the cutting away of the floor by a diagonal belt is avoided by the use of the pulley *A*, which at the same time gives a very large arc of contact of the belt on both the engine and line-shaft pulleys, and if made to slide back and forth it serves as a belt-tightener; on the other hand, the pulley *A* introduces a certain amount of friction.

These last types of station, or some similar design employing a line shaft (that is, a long shaft connected to the engine by belting, from which shaft the various dynamos are driven by separate belts) is generally adopted in cases where one or more large engines are employed to drive a much greater number of dynamos. In fact, it is practically the only way that one engine can drive more than two dynamos. This practice is most common in series arc-lighting stations, which sometimes have as many as fifty or more dynamos. This large number of dynamos is necessitated by the fact that the voltage and number of lights on one circuit are ordinarily limited by practical considerations to from 2,000 to 5,000 volts, corresponding to 40 to 100 lights; hence a large station, feeding several hundred lights, must have a number of dynamos.

The type of station in which the engines are connected to the dynamos by direct coupling, or belting, and one engine drives either one or two dynamos, is the ordinary form employed in low-tension incandescent lighting. In this case there is no necessity for having a large number of dynamos, since the number of lights on one circuit and the size of each dynamo is not limited, as in constant-current arc lighting.

Another reason for not using very large engines driving a number of dynamos for incandescent lighting is the fact that large engines are usually low-speed, and the slight variations in velocity which occur during each stroke are apt to cause disagreeable fluctuations in incandescent lamps, which are extremely sensitive to the least change in the voltage of the dynamo, whereas arc lamps would not be affected by these slight variations. Improvements in the construction of steam-engines, and increase in

speed and in the size and weight of fly-wheels, tend to reduce this objection to large engines for incandescent lighting.

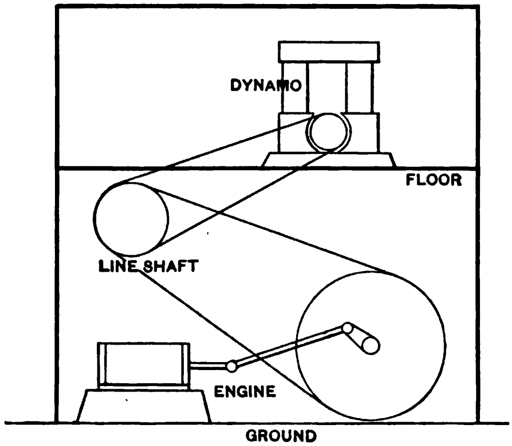


Fig. 2. Arrangement of Engine and Dynamo.

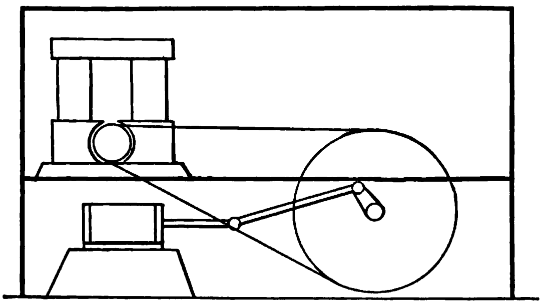


Fig. 3. Arrangement of Engine and Dynamo.

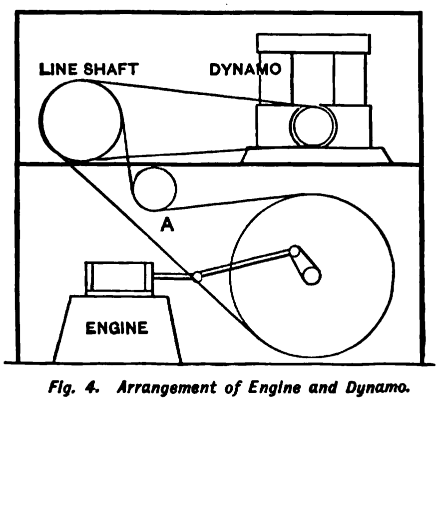


Fig. 4. Arrangement of Engine and Dynamo.

When alternating-current incandescent lighting was introduced, these two types of station were already well developed, and it would seem natural that alternating-current apparatus would have been arranged similar to the low-tension direct-current incandescent apparatus. It happened, however, that for the most part alternating-current apparatus was put into arc-lighting stations, in order that incandescent lights could also be supplied, whereas direct-current incandescent stations were much less likely to adopt in alternating-current machinery. The consequence was that alternating-current apparatus was originally put in alongside of and in a similar manner to arc-lighting machinery; and it is very common to see large stations with a number of arc dynamos and alternators arranged in separate rows or groups, or often mixed indiscriminately together.

The most recent practice, however, is to use large direct-coupled dynamos and engines for alternating as well as direct current incandescent lighting. The engines are of the high-speed marine type specially developed for this service, or low-speed Corliss engines with heavy fly-wheels.

The necessity, from an economical point of view, of using large compound, triple, or even quadruple, expansion engines in the case of stations of considerable magnitude is now generally recognized, and almost all large stations are being adapted to use such engines. Whether these large engines shall drive one or two dynamos directly coupled to each, or a number of dynamos by means of a line-shaft and belting, will depend upon circumstances; but it would seem to be a fact that the use of comparatively small engines, usually of the high-speed type, directly connected by coupling or belting to one or two dynamos, is not the best engineering practice for large stations, although until quite recently it was adopted almost universally for direct-current incandescent lighting, and quite frequently for arc and alternating-current work. These high-speed engines are, however, extremely convenient, occupy small space, and are often the best type to employ for isolated plants, or even central stations of small size.

In England the Willans engine is extensively adopted for central stations, as well as isolated plants. This engine is used in comparatively small sizes of 50 to 300 horse-power, and runs

at very high speeds of 450 to 350 revolutions per minute, so that it is adapted to being directly coupled with the dynamo. These sets, arranged in one or more rows, give a very neat and compact arrangement for a station, since the floor-space occupied by the engine is extremely small.

While these engines are much smaller than those of 1,000 horse-power or more, which are now being used in American and German practice, nevertheless they fulfill the requirement of economy stated above, since they are compound or triple expansion, and show excellent results in smallness of coal consumption. But in large stations of 5,000 or 10,000 horse-power, it is very questionable whether 20 or 30 small engines are desirable on account of the complication and trouble which they would involve. On the other hand, the ordinary rule is that there should be at least one spare machine of each kind, so that the breaking down of any one element shall not cripple the plant. A station with only two units would therefore require each to have the full capacity, and half of the machinery would always be idle; whereas, with a total of four units the spare apparatus is only 25 per cent. Subdivision also avoids the necessity of running the engines lightly loaded for any considerable portion of the time, under which conditions they are very inefficient. A reasonable compromise is therefore to be adopted; and ordinarily there should be from 2 to 4 units for isolated plants and small stations, and from 4 to 8 in large central stations.

Many stations have a larger number of units than are necessary; but this is simply the result of a gradual accumulation of machinery, the capacity of the plant and the available sizes of engine having been much smaller several years ago than at present.

The detailed discussion of engines, belting, dynamos, etc., will be found in Chapters VIII. to XIX., the view taken in the present chapter being only general.

Various plans and suggestions for the arrangement of stations are given in an article by T. Carpenter Smith on "Some Views of Central Station Work," which appeared in *Electricity* (N.Y.), April 27, 1892.

CHAPTER VI.

BUILDINGS FOR ELECTRIC-LIGHT PLANTS.

The building in which an electric-light plant is placed may be designed and built specially for it, or it may be a building already in existence, and built for some other purpose. In the case of a central station the plant usually occupies the entire building, or a large portion of it; whereas, an isolated plant occupies a comparatively small space in the cellar or basement. In any case, the problem of constructing or arranging the building or space comes under the head of architecture rather than of electrical engineering; but it is always very desirable that the electrical engineer should at least be consulted, and have the plan submitted to him. Frequently, however, this is totally disregarded, and the electrical engineer is given a certain place in which to put the machinery; and the result is likely to be very unsatisfactory to all concerned.

This unwise practice is particularly common in regard to isolated plants; and it is the rule, rather than the exception, for the architect to provide a certain room or space which he may arbitrarily think sufficient for the electric-lighting plant. Very often this space is too cramped, or of wrong shape, to allow the machinery to be properly put in. In most cases the difficulty could have been entirely avoided if the electrical engineer had been given an opportunity to make suggestions or modifications in regard to the original plans. The author has visited many plants in which this trouble was very apparent. In one instance the machinery was located in what was little better than a hole in the middle of the cellar, in which ventilation was practically impossible. The consequence was that in summer the temperature of this place often rose as high as 125° F., thus causing the dynamos to run very hot; in fact, their actual output was reduced to about one-half, because they could not generate any more current without being heated above 160° or 170° F., which is the maximum allowable temperature. The attendants were,

of course, thoroughly uncomfortable, and unable to work to advantage. In this case there was plenty of room at the front or back of the basement where windows or direct openings to the outside air could have been had. In many other cases a few feet, or even inches, too little space is provided for the proper arrangement of machinery, resulting in its always working badly. The amount of space required for an isolated plant depends upon the work that it has to do; but usually at least two dynamos and two engines should be installed, and therefore the room required would be 30 to 40 feet long and 20 feet wide, in case the engines are belted to the dynamos, and 25 feet long by 15 feet wide where direct-coupled engines and dynamos were employed. Typical arrangements of an isolated plant are set forth in Volume II. The principal points to be considered in providing a place for an isolated plant are, — sufficient space for effective and convenient arrangement of machinery; ventilation; light; and freedom from excessive dampness.

In regard to the third point, it is obvious that daylight is preferable to any other, and is particularly needed for cleaning or repairing machinery; but it often happens that it is necessary to locate an isolated plant where only artificial light can be obtained, in which case electric lamps may be employed; but it is very important to have at least one or more gas-lights, or other independent lights, in case of accident to the electrical plant, at which time light would be urgently required.

The central station, as already stated, usually has a building of its own largely or entirely devoted to it. If the building is already erected, the duty of the electrical engineer is to arrange it to the best advantage. This will ordinarily require some modification, which should, of course, always be as little as possible, in order to save time and expense. As a usual thing central stations located in buildings originally intended for other purposes have not been very satisfactory. Numerous fires and a great deal of bad engineering can be attributed to this practice. Indeed, central stations have been particularly liable to fires, and this fact should always be borne in mind in designing and constructing the building. In the earlier days of electric lighting this use of second-hand buildings was quite common; but at the present time electric lighting is sufficiently definite and well-established to war-

rant the putting up of a building especially for the purpose, and this is now usually done. In this case the electrical engineer should be consulted in the design and construction of the building, although the details of the work and matters having little or nothing to do with the electrical plant had better be left to architects and builders; in fact, it would be the same mistake for the electrical engineer to interfere in these matters as for the architect to dictate in regard to the electrical machinery.

The space required for a central station depends upon the number and kind of lights to be supplied, and upon the character and arrangement of the machinery. The general arrangement of a station was discussed in the preceding chapter, and it would not be difficult to calculate the size and form of building required in any given case. Two things must be carefully considered, — first, the building must be adapted to the plant to be installed in the beginning; and second, it must be arranged so that enlargement can be made without disarranging or interfering with the plant already in existence. This is usually best secured by providing for expansion in one or two definite directions, the building being extended and the machinery added whenever it is needed, as shown in Fig. 5. The ordinary building required where engines are belted to the dynamos should be at least 40 or 50 feet wide for the machinery, and 25 to 40 more for the boilers, and the length will depend simply upon the number of machines put in. This same width would also be suitable for direct-coupled engines and dynamos. In fact, a building of less width than this would not usually be desirable, even though it might be possible to arrange the machinery in a narrower space. The character of the building depends upon the size of the plant, its location, the kind of buildings surrounding it, and other local conditions; but usually a simple, substantial structure is all that is required. This matter can only be determined by the judgment of the engineer and architect.

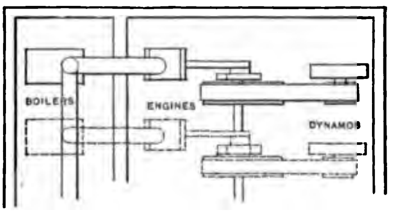


Fig. 5. Plan of Station arranged for extension.

It is customary to build a station of wood, or of wood and brick, in a village or small town; of brick with a smaller amount of

wood for larger towns; and entirely of brick or stone, in order to to be more substantial and ornamental, in a large city.

Let us now briefly consider the foundation, walls, and other parts of the building, which, although not strictly a part of electrical engineering, nevertheless should be understood and considered by the electrical engineer in a general way.

FOUNDATIONS.

The foundation is the most important part of a building, according to Franklin, and this is particularly true of electric-lighting stations which contain heavy machinery. The electric-light engineer must therefore exercise the greatest care to secure substantial and enduring foundations. The particular kind of foundations will depend upon the character of the ground and other local conditions. Cases may occur varying from stations located on piles to stations which are set upon solid rock. Certain general engineering principles apply, however, to almost all cases, and are reasonably definite and reliable. Foundations should not be likely to be affected injuriously by frost, water, air, weather, or other mechanical or chemical action. Foundations may be displaced vertically by compression or settling of the ground, or horizontally by the sliding of the substrata on one another. Almost all foundations are liable to a slight amount of settling which may be perfectly legitimate; but any excessive or irregular settling of the different parts of the building is, of course, very objectionable. A careful investigation should, therefore, be made of the character of the ground by driving piles or iron tubes (ordinary gas-pipe), excavating, etc., to ascertain exactly what the ground will support, and what kind of foundation is required.

Foundations are either natural or artificial. The former are those in which there is solid rock or sufficiently substantial soil *in situ* to support the building without any reënforcement.

Artificial foundations are those in which piles, iron beams, caissons, or other special means are employed to reënforce soil which is not sufficiently firm itself.

The drainage of foundation should be carefully attended to. Means should be provided to free the foundation, excavation, and trenches from water accumulations, either by connections to

the regular town drainage system, or by temporary outlets, pumps, etc. It is better to divert springs and water channels, than to attempt to dam them away from foundations; because the latter requires a perfectly impervious wall, which is difficult to make and is likely to crack. The foundation for any important structure should be carefully tested, as already stated, by driving piles, digging deep pits at various points of the foundation site, or by augur boring, which brings up samples of the various soils it passes through. An actual test of the foundation soil may be made by applying to a certain portion of the ground a certain weight per square foot, corresponding to the weight of the building, etc., to be carried. In addition to these tests, one may be guided by the general data of the safe bearing-power of soils, etc., the values for which have been obtained by experience. These are given in the following table: —

HARD ROCK, in thick strata, can carry 200 tons per square foot.
GRAVEL AND COARSE SAND, well cemented with clay, protected from water, 4 to 8 tons.
SAND, compact and not liable to lateral disturbance, 4 to 8 tons.
SAND, clean, dry, 2 to 4 tons.
CLAY, in thick beds, always dry, 4 to 6 tons.
CLAY, moderately dry, 2 to 4 tons.
CLAY, soft, from 1 to 1.5 tons.
QUICKSAND, alluvial soil, etc., according to dampness, .5 to 1 ton.

Mud, quicksand, and other semi-liquid soils will, according to Rankine,* support per unit of area a weight equal to $wh\left(\frac{1+\sin a}{1-\sin a}\right)^2$, in which w is the weight of a unit volume of soil, h is the depth of immersion, and a is the angle of repose of the soil. It is not wise, however, to rely much upon the bearing-power of such soils; and it is better either to remove them entirely, to sink piles or caissons through them to a solid substratum, or to consolidate the soil by adding sand, earth, or stone.

In case the ground is so soft or unreliable as to require the driving of piles, these may be of hemlock, spruce, oak, yellow pine, or other suitable and available wood, perfectly straight and round, 30 to 40 feet long, and not less than 10 inches diameter at the smaller end, and 14 inches at the larger. Piles should be driven

* Rankine's *Civil Engineering*, p. 379.

perfectly vertically, and after being driven should have their heads sawed off squarely to a uniform height. This level should be below the lowest point at which the water in the soil is known to stand; otherwise the heads of the piles will quickly rot where they project above the water-level. Piles should be capped with a timber "crib," on which rest the foundation stones. This crib usually consists of 12×12 inch spruce or yellow pine, placed longitudinally, and treenailed to the piles, the space between the caps being filled with concrete.

Rankine's formula for the supporting-power of piles is:—

$$P = \sqrt{\frac{4\,Whse}{l} + \frac{4\,d^2s^2e^2}{l^2}} - \frac{2\,dse}{l},$$

in which P is total supporting-power in tons, W is weight of pile-driver ram in tons, h is height of fall in feet, s is section of pile in square feet, e is coefficient of elasticity of pile in tons per square foot, l is length of pile in feet, and d is distance in feet that the pile is moved by the last blow. A factor of safety of from 5 to 10 should be allowed in using the above formula.

Metal piles made of wrought or cast iron are sometimes used.

Excavating.—It is well to excavate the entire space under the engine-room to a depth of 8 or 10 feet, so as to get clear head-room in the basement. Excavate for all side, cross, and gable walls, all foundations, and also central space between boilers to form a basement under the boiler-room for ash and coal handling apparatus, flues, and pipes. The excavated material usually increases considerably in bulk, ordinary earth occupying about one-quarter more space, rock about one-half more; but loose soils may actually compress into less space than occupied in their natural position. Excavating is measured and priced by the cubic yard, and the ordinary single cart-load is equal to one cubic yard. The cost of excavating depends upon the hardness of the soil and depth of excavation, etc. The maximum distance that material can be thrown up with a shovel is 6 feet; hence, for greater depth, intermediate staging, or levels, must be provided, or the material must be carted out on an incline, or else hoisted. In loose ground a man can shovel about 10 cubic yards per day of 10 working-hours; in stiff clay or firm gravel, about 6 yards; in hard ground, where picking is required, 4 yards. One man can

remove 10 cubic yards to a distance of 20 yards, by means of a wheelbarrow, in one day. In excavating in compact soil, the sides are supported by short rough boards called "poling-boards," which are laid vertically against the sides, at intervals, and kept in place by cross-struts of timber.

If the excavation be a cellar, the sides must be sustained by inclined "shores" footed upon the excavated bottom. In very loose soil, long poling-boards are placed horizontally close together, and usually held in place by short vertical wales of stout plank and struts of timber across the trench. Excavations should be 6 inches wider on each side than the width of the foundation base, and the bottom should be made perfectly level; or, if on rising ground, in as long benches or steps as the gradient will allow. Trenches should be 3 feet wide if 8 or 9 feet deep, and 4 feet wide if over 9 feet deep.

Underfooting. — Foundation trenches are sometimes filled to a depth of 2 feet or more with broken stone, gravel, sand, and concrete, well rammed in convenient layers. This greatly increases the bearing-strength of the soil. When concrete is used, it should be made of good hard-setting lime, or hydraulic cement, so that it may act as a monolithic structure, in order to distribute the pressure over its whole area.

Foundation Footings. — The base or footing of the foundation projects considerably beyond the walls themselves, in order to distribute the pressure over a greater area. The following points should be taken into consideration : —

1. The area should be sufficient to impose upon the subsoil a pressure which it will safely bear per unit of area.

2. The foundation should support its load at or near its center.

3. The upper surface should be made horizontal in one plane, if possible, or in benches on rising ground.

Three kinds of foundation are employed : —

1. Those in which the foundation is of uniform width.

2. Those in which the foundation is wide where piers or pilasters occur, and narrow between them where the load is much less.

3. Those which consist of isolated parts not connected with each other. In this last case the excavation consists of pits instead of trenches.

In ordinary practice the footing-courses, upon which the walls of the building proper rest, consist of blocks or slabs of stone as large as are available and convenient to handle. Footings of brick or concrete are also used in very soft soils; footings consisting of timber-grillage are often employed. A grillage of iron or steel beams has also been used successfully. The inclination or angle, *a* (Fig. 6), of footing should be about as follows:

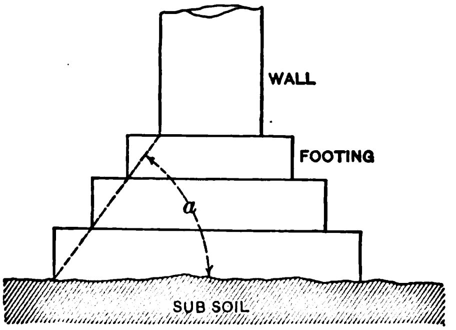


Fig. 6. Angle for Foundation Footing.

For metal footings 75°, for stone 60°, for concrete 45°, and for brick 30°. Damp-proof courses of slate, or layers of asphalt, are laid in or on the foundations or lower walls to prevent moisture arising or penetrating by capillary action.

The foundations for the machinery should be entirely separate from those of the walls and other parts of the building. The question of foundations for machinery is particularly troublesome, because it involves the problem of preventing the transmission of vibrations to adjoining rooms or buildings. Electrical machinery, and the engines, shafting, etc., used in connection with it, usually run at a high speed; and this fact aggravates the vibration. The character of the ground upon which the foundations rest determines how far and how intensely the vibrations are conveyed. Sand or soft earth transmits them poorly; firm earths transmit quite well, and rock almost perfectly. In cases where vibrations are likely to be transmitted and cause annoyance, various materials have been used to deaden them, such as sand, wood, hair-felt, mineral wool, and asphaltic concrete. In rock or firm earth one plan is to excavate a pit two or three feet deeper and two or three feet wider on all sides than the foundations are intended to be.

A bed of the same thickness of sand is then put in the bottom, and the foundations are built upon this, and are filled around with sand. Another way is to lay foundations upon a crib of 2″ × 12″ wooden plank, and cap the foundations with timber; but wood transmits vibration too well to be very effective for deadening purposes. On solid rock, where there is great fear of transmitting vibrations, the rock may be excavated six feet deeper than the foundations, and filled in with hair-felt or mineral wool, upon which the foundation is built. The most satisfactory solution of this problem seems to be the use of bituminous or asphaltic con-

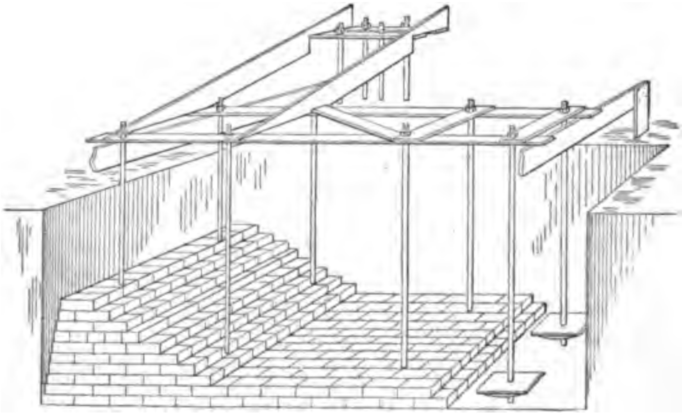


Fig. 7. Template for use in Building Machinery Foundations.

crete, which is made to form the lower one, or two feet of the foundations, the remainder being brickwork, or ordinary concrete with a bluestone cap. This has been extensively tried in France for steam-hammers, engines, dynamos, etc., with excellent results.

The machinery foundations themselves consist of a mass of brickwork, stone-masonry, or concrete, upon which the machinery is placed, the latter being usually held firmly in place by bolts passing entirely through the mass.

These bolts are built into the foundations, the proper positions for them being determined by a wooden frame or template, as indicated in Fig. 7. The brickwork for machinery foundations should consist of hard-burned bricks of first quality, laid in good cement-mortar. Ordinary lime-mortar is entirely unfit for the purpose, being likely to crumble away under the effect of the vibrations

caused by the machinery. Brick or concrete foundations should be finished with a cap or slab of bluestone. This tends to hold the foundations together, and also forms a level surface upon which to set the machinery. If the engine is self-contained, that is, provided with a cast-iron base, a stone cap for brick foundations may be dispensed with.

Walls. — The walls of the building may consist of either wood, brick, stone, or iron, depending upon the location and size of the building, and other circumstances. The walls of a station in a small town may be of wood, as already stated; but brick is preferable for many reasons. If wooden walls are adopted, they may properly consist of vertical posts 8 inches square or larger, and 10 feet between centers. These support the roof timbers and wall proper. The latter consists of spruce plank 3 inches thick, grooved and splined, nailed horizontally against the posts. Outside of this one-inch boarding is laid vertically, and the cracks battened with strips of wood; or the outside of the wall may be covered with clapboards.

Fig. 8 shows the standard type of electric-light station recommended by the Boston Manufacturers' Mutual Fire Insurance Co., and designed by Mr. C. J. H. Woodbury. The right-hand side shows a wooden wall, and the left-hand side a brick wall construction. If the walls be constructed of brick, they should be at least 12 inches thick, even in small stations, and 16 or 20 inches thick in large stations. There should be a pilaster at each roof truss, having 8 inches projection and 24 inch face.

The bricks used should be hard burned, and have clean, sharp edges, no salmon or light-colored brick being allowed. The common size of bricks in Eastern cities of the United States is 8¼ by 4 by 2 inches, equal to 66 cubic inches, weighing about 4½ lbs., or 2¼ tons per thousand. A pressed brick of the same size will average about 5 lbs. each. The crushing strength of bricks varies greatly. A soft one will crush at about 500 or 1,000 lbs. per square inch, while a first-rate machine-pressed brick will not crush with less than 3,000 to 5,000 lbs. per square inch. Cracking and splitting, however, usually commence at about one-half the crushing load; and to be really safe the load should not exceed one-tenth of the crushing strength. Bricks may be laid in common lime mortar or cement mortar; the latter is much prefer-

able, particularly if the walls are subjected to vibration, or are required to carry considerable weight, in cases where machinery is put upon floors supported by the walls, or where traveling cranes are used. Common mortar consists of one part of quicklime and three to four parts of sand by bulk. About 20 cubic feet of mortar are sufficient to lay a thousand brick with coarse joints of ⅜ inch, usual in interior walls. In such cases one thousand brick make 2 cubic yards of massive work, nearly one-third of the volume being mortar. For outside or other joints which show,

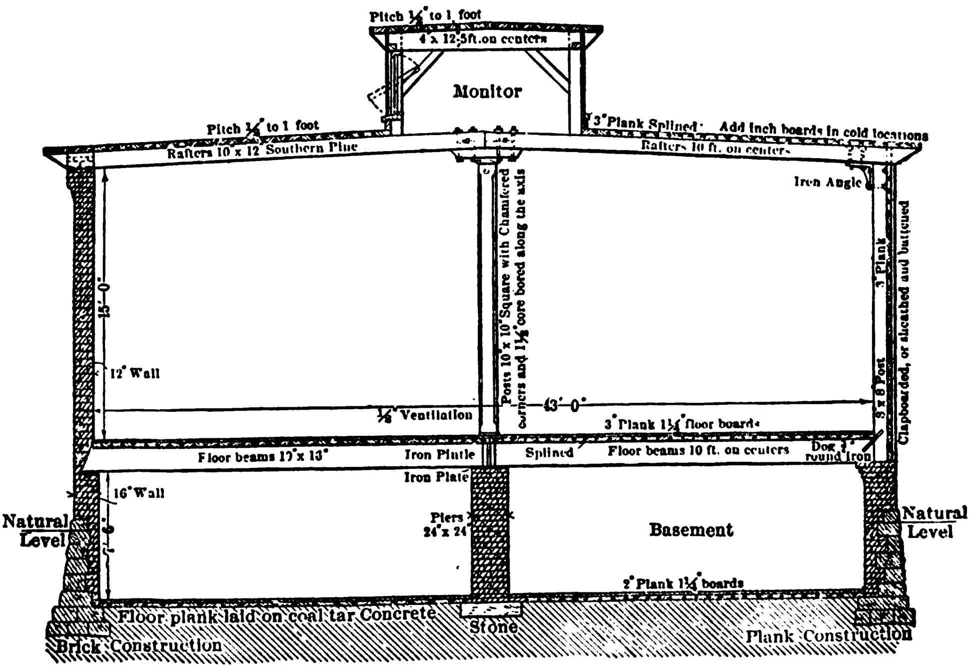


Fig. 8. Standard Electric-Light Station.

a whiter and thinner layer of mortar is used, made of one part of lime to 2½ or 3½ parts of sand. It is necessary to protect quicklime from moisture, as even the moisture of the air will cause it to undergo the process of air-slaking. The average weight of common hardened mortar is 105 to 115 lbs. per cubic foot. The crushing strength of good common mortar six months old is from 125 to 200 lbs. per square inch. Both the sand and lime of lime mortar should be free from clay and soil. Mortar should not be mixed upon the surface of clay ground; but a rough

board, brick, or stone platform should be interposed. Pit sand sifted is excellent for mortar. Its sharp angles make with the lime a more coherent mass than the rounded grains of river or sea sand, the latter also having the objection of containing salt, which is very difficult to remove. One barrel of unslaked lime (230 lbs.) will make about one cubic yard of ordinary mortar. Mortar should be applied wetter in hot than in cold weather.

As already stated, cement mortar is preferable to common mortar, when required to stand considerable weight or vibration. This consists of 1 part of cement and 2 to 4 parts of sand. It is very important that the cement and sand be thoroughly mixed.

A bricklayer and a laborer to keep him well supplied with materials will, in common house walls, lay an average of about 1,200 to 1,500 brick per day of 10 working hours; in good, ordinary street fronts 700 to 1,000, and on very fine work with angles, etc., 150 to 300. In plain massive engineering work he should average about 1,500 per day. Higher figures than these are sometimes given by engineering authorities, but it is doubtful if they can be realized. This may partly be accounted for by the fact that the working-day is now only 9 or even 8 hours, instead of 10, which was formerly the rule.

Stone walls for stations are used in large cities where more substantial and ornamental structures are desired. The kind of stone employed for the purpose will depend upon what is most available, but would ordinarily be sandstone, limestone, or granite, laid in cement mortar. The cost of good stone masonry of course varies greatly, but is usually between $20 and $40 per cubic yard.

Iron would not be a particularly suitable material for the walls of a central station, because it would transmit too readily the heat and cold; it would make the supporting and insulation of the wires, switches, etc., difficult; and would act as a sounding board for noise and vibration. It would have the advantage, however, of being absolutely fireproof. If iron were used, it would be applied in the form of cast plates or rolled sheet iron, which latter would ordinarily be corrugated.

Roofs. — The roof beams, or trusses which support the roof proper, may consist of either wood or iron, the former having the advantage of cheapness, the latter being stronger and fireproof.

The simple roof construction shown in Fig. 8, consisting of rafters 10 or 12 inches square and 10 feet between centers, will answer for small stations. For larger stations regular roof trusses of any of the well-known forms should be used. Iron trusses may also be employed. In any case it is desirable to have a louver or monitor, with side ventilators on the roof, as represented in Fig. 8. Whether the roof trusses be of wood or iron, the roof itself may be made of 3-inch plank splined, having a proper pitch, and covered with slate, tin, or tar and gravel.

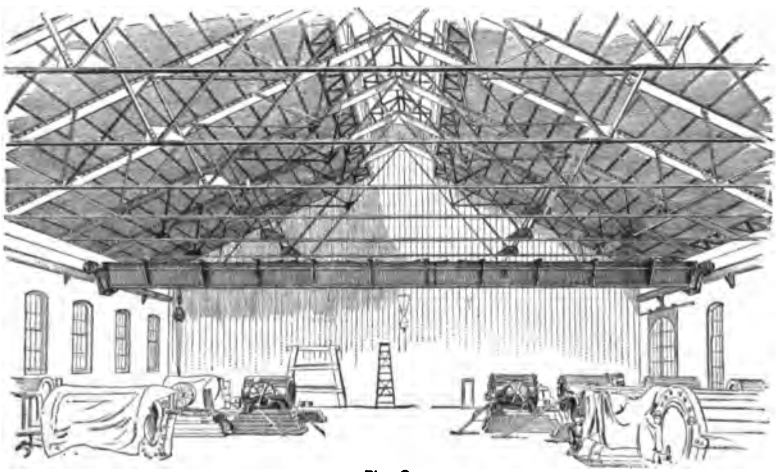


Fig. 9.

In many instances, stations have been provided with roofs entirely constructed of iron. Fig. 9 shows one of a number of iron roofs specially built for electric-light stations by the Berlin Iron Bridge Co. of Connecticut. These are fireproof and neat in appearance, but they require a ceiling or lining of some suitable material, to prevent water from being condensed on the roof in cold weather and dripping upon the dynamos, which would be very objectionable. Several methods of overcoming this difficulty have been devised, some of which are given in the *Electrical Engineer* (N.Y.) of Jan. 20, and March 9, 1892.

Floors. — The engine and dynamo room floor should consist of two layers of plank, the first of yellow or Norway pine splined, and the second of $\frac{7}{8}$ inch maple. The boards of the second floor should not be over 4 inches in width, and should be blind nailed.

A brick or cement floor is very undesirable for a room containing machinery, for the reason that the grit produced by wear is stirred up by walking or sweeping, thereby getting into the bearings and other parts of the machinery, and causing them to wear and heat. Some form of wooden surface for the floor should be provided in rooms containing running machinery. In the case of dynamos generating high-tension currents, another important reason for using wooden, and not brick or cement, floors is the fact that the latter would be apt to cause a man standing on them to have a good electrical connection with the ground, and accidental contact with a dynamo or wire might injure or even kill him. In fact, where currents of over 500 volts are generated, some special means should be carefully provided for securing perfect insulation of the floor in the neighborhood of dynamos, switchboards, and other places where men have to handle the high-tension apparatus. This floor may consist of thick boards or planks having the pores filled with oil, paraffine, or other substance to prevent absorption of moisture. These planks should be held by blind nailing, or by driving the nail heads below the surface three quarters of an inch or more, the holes being filled afterwards with wooden plugs, in order that persons may not, by accidental contact with the nails, be hurt. Where extremely high voltages of several thousand volts are employed, a special insulated floor mounted on glass or other form of insulators should be constructed. A well insulated floor is the best safeguard against shocks to those working about high-tension machinery, and is well worth putting in, although it is not an absolute preventive of accident.

The floor of the boiler-room should be made of brick, concrete, or cement, in order to be fireproof, as there is not the same objection to grit and electrical conduction which makes these materials unsuitable for the floors of the engine and dynamo rooms.

Division of Station Building. — In the station building space must be provided for the various parts of the plant and business as follows: The boiler-house may be a separate building, which in some respects is desirable to remove fire risk and dirt. In any case a brick wall or partition should be interposed between the boiler-room and the other parts of the building, in order to shut off danger of fire; and this partition should be impervious without

any direct opening into the engine and dynamo room, in order to exclude dirt and grit. If a doorway is needed, it should be kept closed.

In or near the boiler-room, space should be provided for the coal, ashes, pumps, heaters, etc.; and it is important that this space should be suitably and conveniently arranged, the pumps, for example, being put in a separate room. The engine and dynamo rooms may be combined or separate, according to the arrangement of the machinery. It should be remembered that these machines are the most valuable, delicate, and important parts of the plant, and should have ample space, suitably located and arranged. Facilities should be provided for handling the machinery conveniently. The best plan is to have an overhead traveling-crane, as shown in Fig. 9, by which any machine may be carried and placed wherever desired. The advantage of this in the long run is well worth the expense, where the number or weight of machines is great. A general office for the officers, clerks, and other business employees should be provided, which may be divided into several rooms in the case of large stations. A supply or storage room of ample size is needed in every station, and also a workshop or repair department.

In case overhead wires are used to distribute the current, a wire tower should be built on top of the building, usually at one end or corner. This is considered in connection with the subject of overhead wires in Volume II. If the current is distributed by underground conductors, a cable-room should be arranged where the conduits lead out of the building. If a storage battery be a part of the plant, a suitable room or space must be provided for it. This should be shut off as far as possible from the machinery and instruments, in order that the fumes from the battery may not corrode them. Several small rooms are usually needed for testing and adjusting lamps, meters, measuring-instruments, etc., the number and size of these depending upon the character and magnitude of the business.

All these different rooms and departments should be carefully considered and provided for in making the original plans of the building. It is not wise to build what appears to be a sufficiently large structure, and then try to fit in the various rooms and spaces afterwards.

Stairs and Elevators should be placed outside where possible, or, if inside the building, stairs should be completely partitioned off from the room below with brick or hard wood, and provided with self-closing doors, hung at the bottom of the flight. Elevators should be completely partioned off by brick walls, or not incased at all, but provided with approved self-closing hatches.

Inside Finish. — There should be as little as possible extra inside finish, such as sheathing, lath, plaster, etc., that would leave concealed places, or add inflammable material to the station. If the building be of brick, the inside should be left perfectly plain, or finished with paint to cover the roughness. If constructed of wood, the timbers and boarding should be dressed on the inside, if a rough finish is undesirable.

It is better to leave the inside walls and ceilings plain and open, and sacrifice appearance for safety against fire, which central stations seem to have been particularly liable to. The use of tiles on the interior walls, which is quite common in English and Continental stations, gives a finish which is excellent in appearance and cleanliness; but it would ordinarily be looked upon as an extravagance in this country, where first cost is considered so important.

Fire Doors and Shutters may be made of two thicknesses of one-inch matched boards, with a layer of asbestus between, and nailed together with French nails. The boards should run diagonally, the two sides in opposite directions, to give strength. The covering should be tin, laid on with flat lock, securely nailed under the lap, covering both sides and edges completely. The frame or casing should be as securely tin-clad as the door or shutter, which should be provided with a strong latch, to hold it in place. These doors are claimed to be better than those entirely made of wrought iron, for the reason that they do not warp so much when heated. Fire doors and shutters of corrugated sheet iron are less likely to warp than flat plates, and are frequently employed.

Fire Apparatus. — Automatic sprinklers may be arranged about the building; but they would be rather objectionable in the dynamo or supply rooms, as any drip from them would cause serious injury: but hydrants, pumps, fire-hose, and fire-buckets, the last being kept full of water, should be provided in stations

to an extent corresponding to the importance of the station, and the danger of fire.

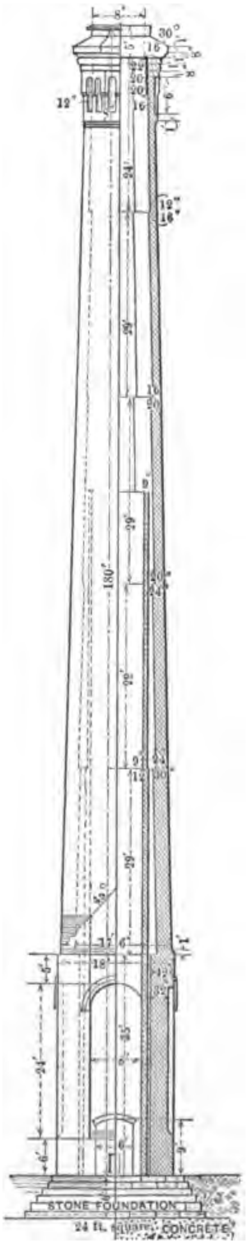


Fig. 10. Brick Chimney.

The Chimney is usually a very prominent feature of an electric-light station, and its design and construction demand considerable engineering ability. Great difference of opinion exists as to the relative desirability of brick or iron smoke-stacks. The former is more substantial, architecturally better in appearance, and does not lose so much heat by radiation; but the latter is cheaper in first cost, occupies less space, does not require such extremely solid foundation, and is not so likely to crack and allow cold air to leak in as the former. A brick chimney should have two substantial walls, with an air-space between, in order to prevent the cooling and the cracking of the inner wall or flue proper.

The right side of Fig. 10 shows a section, and the left side an elevation, of a standard brick chimney, dimensions, etc. being given. The almost universal rule is that the external diameter of a brick chimney at the bottom should be at least one-tenth of the height, in order to give sufficient stability to resist wind-pressure. The "batter," or taper, of a brick chimney should be from $\frac{1}{8}$ to $\frac{1}{4}$ inch to the foot on each side. Iron stacks should be lined with brick throughout their entire height; and they are prevented from overturning by strong lugs and bolts at the bottom, and by stays or braces of iron rod fastened to an angle iron ring at two-thirds the height of the stack, and spreading in three or more directions at about an angle of 45° to the horizontal, being securely attached to suitable objects. Iron stacks must be kept

well painted, to prevent rust. In some cases self-supporting iron chimneys, consisting of sections bolted together, have been used successfully. These have the advantage of not requiring guys or braces of any kind. The height of chimney required for a central station or large isolated plant would be from 100 to 200 feet, depending upon the boiler-power. In the case of small isolated plants, the chimney may merely form part of the walls of the building.

For further information regarding foundations, buildings, etc., the reader is referred to special treatises on the subject; such as *Masonry Construction*, by J. O. Baker, Wiley, N.Y., 1891; *Building Construction*, Lippincott, Philadelphia. A paper by William Brophy on "Fire in Central Stations and the Question of Insurance," *Electrical Engineer*, N.Y., Aug. 23, 1893, gives the history of fires in central stations, and suggestions as to their prevention. Papers by C. J. Field on "An Ideal Central Power Station," *Electrical World*, Dec. 31, 1892, and by M. D. Law on "The Perfect Arc Central Station," *Electrical World*, Aug. 17, 1889, contain much practical information on the construction and arrangement of stations. *Continental Electric Light Central Stations*, by Kellingworth Hedges, Spon, London and New York, 1892, contains illustrations and descriptions of most of the important European stations at the time of the Frankfort Electrical Exposition of 1891.

CHAPTER VII.

POSSIBLE SOURCES OF ELECTRICAL ENERGY.

THE source from which to obtain electrical energy is obviously a matter of prime importance. It is, however, a most difficult problem, and one which is undergoing great change and progress at the present time. The difficulty of the problem is increased by the fact that it involves some of the deepest principles and finest points, not only in mechanical and electrical engineering, but also in chemistry, being, as it were, on the border-line between these great branches of applied science.

The interest and importance attached to this subject make it worth while, therefore, to carefully consider and compare the various methods of generating electricity, including not only those which are already in common and successful use, but also possible methods, even though they be not yet practical. These may be arranged as shown in the accompanying table:—

Possible Methods of Generating Electrical Energy.

Natural Sources of Energy.	Used in following apparatus.	Produce.	Used in following apparatus.	Produce.
Fuel, Including Coal, Oil, Natural Gas, Wood.	Voltaic battery, Metallurgical apparatus,	Electrical energy, Zinc or other metal,	Voltaic battery,	Electrical energy.
	Thermo-electric battery, Thermo-magnetic generator,	Electrical energy,		
Heat of Sun, **Heat of Earth,**	Steam-engine, Gas-engine, Hot-air engine,	Mechanical Energy.	Dynamo, Electrostatic machine.	Electrical energy.
Water Falls,	Water-wheel,			
Tides,	Water-wheel,			
Waves,	Wave-motor,			
Wind.	Windmill,			
Animal Power.	Treadmill or crank.			

This table shows the natural sources of energy that are at all available, all of which, with the exception of the power of the

tides and the internal heat of the earth, are derived from the radiant energy supplied to the earth by the sun. Of these possible sources only two — fuel and water-power — are now used to any extent to produce electrical energy, or, indeed, any other form of energy for any purpose requiring considerable power.

For various reasons, chiefly unreliability, the other sources are not practical.

Animal-power can be used to generate electrical energy, as in the case of a small dynamo driven by hand; but the power is very small. Even a strong horse working in a treadmill could hardly drive a dynamo of sufficient capacity to supply ten ordinary incandescent lamps. In short, animal-power is obviously inadequate for heavy work. Nevertheless, the electrical engineer is not in a position to speak contemptuously of animal-power, since it is only within a very few years that electric-power produced by the best methods has been able to compete successfully with horses in the propulsion of street-cars.

Wind-power is cheap and simple; but it is proverbially unreliable and unsteady, and therefore requires the use of storage batteries and rather complicated automatic devices for connecting the windmill, dynamo, and storage battery. Mr. C. F. Brush has for several years had a wind-power electric plant in his private grounds at Cleveland, Ohio.* A recent article gives data of construction, cost, and operation of a number of such plants.† Wind-power may answer for small private plants, but not for large commercial works. This subject is treated further in Chapter XIV.

Wave-power is, of course, primarily derived from the wind, but it is not quite so unreliable or unsteady. There are, however, great difficulties in its use. It is not practicable to drive a dynamo directly by a wave-motor. It would be better to pump water to a reservoir, and run the dynamo by a water-wheel; but it is very doubtful if any such plant would be very satisfactory.

The power of the tides is really due to the energy of rotation of the earth on its axis; and, theoretically, any resistance to the flow of the tides produces an infinitesimal slowing down of the earth. Tide-power is almost the only natural power not derived from the sun, and is more practical than wave-power. The usual

* *The Electrical Engineer*, Dec. 24, 1890.

† "Wind Mills for Electric Lighting," G. H. Morse, *Elec. World*, June 10, 1893.

way of obtaining it is to allow the water to run into a pond at high tide, and when the tide begins to run out, a gate automatically closes. When the water-level outside falls a sufficient amount, the water in the pond is allowed to flow out, and to operate a turbine-wheel which drives a dynamo.

This power is much less likely to fail than ordinary water-power, being nearly constant throughout the year, except that ice would be apt to cause trouble. The disadvantages are that the turbine can only be run twice in the twenty-four hours for about four hours each time, and the times of these periods change with each day. This would necessitate the use of a storage battery.

It is evident that this power is only available on the seacoast, and then only at places having a large rise and fall of tide, which must be at least 6 feet, and should be 10 or 12, since the average head is considerably less. It is not likely that this source of energy will ever be largely used except in certain localities for small amounts of power.

Water-power is, as already stated, one of the two great sources of power used for large and important work. It is very simple in principle, and involves no very difficult theoretical or practical questions. The evaporative action of the sun lifts up, so to speak, the water, which afterward condenses, and falls as rain upon the land; and in running to the sea in the form of rivers or streams it is capable of giving mechanical energy in proportion to its weight and the height through which it descends, by passing it through a turbine, or other form of water-wheel, which, in turn, drives a dynamo that generates electricity. Water-power possesses the advantages of simplicity and cheapness; but it has the disadvantage of liability to fail during droughts in summer, and is subject to troubles from ice and floods in winter and spring. Water-power is usually not so cheap as is supposed, largely because of its unreliability; and frequently steam-power is preferred, even where water-power is available. The amount and accessibility of water-power are somewhat limited; and, with the exception of Niagara Falls, most of the water-power in the thickly settled parts of America and Europe is already used.

For example, the water-power at Holyoke, Mass., Rochester, N.Y., and Patterson, N.J., which are about the largest in their

respective States, are already nearly all used. Some countries, like Switzerland, have more than enough for their needs; but others, like England, have but an insignificant fraction of what is required. The long-distance transmission of electrical energy from enormous water-powers like Niagara will tend to overcome this limitation. But it is a question even then whether electric-power from Niagara can be supplied at a distance of 100 miles, for example, as cheaply as steam-power. The great experiment now being tried at Niagara, which will probably be successful, will not, after all, greatly affect the question of power for the country at large.

The Heat of the Sun is a source of energy of enormous quantity, the total heat received per annum from the sun by the earth being equivalent to the combustion of a layer of coal eight inches thick covering the entire surface of the globe. A large part of this heat is, however, intercepted by clouds and the atmosphere. Moreover, the heat requires concentration or accumulation in order to develop any considerable power, the average quantity of heat received per square yard upon a clear day being equal to about one horse-power. Ericsson and others have focussed the sun's heat by lenses or mirrors, and operated engines of a few horse-power. This source of energy has the insuperable difficulty of being interrupted by cloudy weather for weeks at a time. If this heat were employed to operate steam-, gas-, or hot-air engines, or thermo-electric or thermomagnetic generators, the case would be very similar to the use in these apparatus of the heat obtained from fuel, which will be discussed later.

Heat of the Earth. — This is also a possible source of energy of vast quantity. It manifests itself naturally in the case of thermal springs, volcanoes, etc. It is made evident artificially in deep mines and oil-wells. A well near Leipsic, Germany, is 5,740 feet deep, and has a temperature of 135.5° F. at the bottom; and another at Wheeling, W. Va., is 4,500 feet deep, and has a temperature of 110.3° F. at the bottom.* In many other places, particularly near active or extinct volcanoes, the temperature would be much higher at a given depth. This cannot, however, be said to be a practical source of energy at

* See paper by Professor W. Hallock, *American Association for the Advancement of Science*, vol. xl., 1891.

present; but it is by no means impossible that deep holes might be bored in favorable localities for the express purpose of obtaining heat from the earth. To obtain mechanical or electrical power from this heat would, as in the case of the sun's heat, be a matter similar to the utilization of the heat of fuel, which is the next subject to consider.

Fuel. — The use of fuel in the production of electrical energy is one of the most momentous and difficult problems presented to the human mind. Even a fairly satisfactory solution of it requires the employment of some of the most important principles in science and engineering, and has a very great effect upon civilization. A direct and satisfactory solution of this grand problem is the hope and aim of many of the greatest living men of science; and its probable effect would be to revolutionize present methods in agriculture, mining, manufacturing, commerce, and even domestic economy.

The energy in fuel exists in the form of chemical affinity; that is, the atoms of carbon and hydrogen of which it is composed have a very strong affinity for oxygen; and under proper conditions combination takes place, the chemical energy possessed by the fuel being converted into some other form of energy, usually that of heat. This energy in the fuel is latent or potential energy similar to that of a stretched spring, which is entirely inactive until it is released. In fact, carbon is one of the most inert of all substances at ordinary temperatures, and will exist without sensible action or change for centuries. This potential energy of fuel is stored in it by the action of the sun's rays upon plant-cells in which carbon dioxide is decomposed, carbonaceous material being formed and oxygen set free. This carbonaceous material can be used immediately as fuel, as in the case of wood; or it may be converted into peat, coal, etc., by long-continued natural processes.

The ordinary method of obtaining energy from fuel is that of combustion, which consists in causing the carbon to combine with the oxygen of the air, producing carbon dioxide again, and generating an enormous amount of energy in the form of heat. This combination does not ordinarily take place except at a high temperature, usually about a red heat, which is the condition necessary for the action.

Steam-Engines. — The heat energy produced by combustion can be applied in various ways to produce mechanical or electrical energy, the most common method being to cause it to evaporate water in a boiler, the steam produced being used in the cylinder of a steam-engine to move the piston and produce mechanical power. In the gas-engine the fuel in the form of gas (which may be either natural gas or some liquid or solid form of fuel previously converted into gas) is caused to combine with the oxygen of the air directly in the cylinder of a suitable machine, the combined gases being raised to a high pressure by the combustion, thereby actuating the engine. These and other similar forms of machine are called heat-engines; and with the exception of water-wheels they are practically the only prime-movers or original sources of power used for generating electrical energy or for any other useful purpose, and they have contributed more than any other factor to modern civilization.

Nevertheless, there are certain inherent theoretical and practical difficulties which apparently leave much room for radical improvement in the production of mechanical and electrical energy from fuel. In the first place, the method now ordinarily employed to generate electricity is very roundabout. It consists, first, in burning coal under a boiler; second, evaporating water in the boiler; third, conveying the steam to the cylinder of the engine; fourth, allowing the steam to expand and move the piston; fifth, transmitting the motion of the piston by means of mechanism to produce rotation of the shaft of the engine; sixth, causing the rotation of the dynamo by mechanical connection with the engine; seventh, generating electric currents in the dynamo by revolving conductors in a magnetic field. Thus we see that there are seven distinct steps in the process of generating electricity, for which three large and expensive pieces of apparatus are required; viz., boiler, steam-engine, and dynamo, each of which has a great many parts and requires considerable attention; and these three main pieces of apparatus have to be connected together by piping, mechanism, etc., which still further complicate the plant.

In addition to the very objectionable indirectness of the present method of generating electricity with the steam-engine and dynamo, there is a theoretical limitation to the efficiency of a

heat-engine which is still more serious. The greatest possible efficiency of any heat-engine is expressed by the formula $E = \frac{T_1 - T_2}{T_1}$, in which T_1 is the initial absolute temperature and T_2 the final absolute temperature. This formula is derived from the second law of thermo-dynamics, and signifies that if steam or hot gases enter the cylinder of a heat-engine, and begin to act at a temperature T_1, and cease to act and pass out at a temperature T_2, then the maximum possible efficiency of that engine is given by the formula. For example, an ordinary non-condensing engine receiving steam at 80 lbs. pressure, which is equivalent to a temperature of 162° C., and exhausting or giving out steam at the atmospheric pressure of 15 lbs., equivalent to 100° C., would have an efficiency

$$= \frac{(273 + 162) - (273 + 100)}{273 + 162} = 14\tfrac{1}{4} \text{ per cent.}$$

This efficiency is theoretical, and takes no account of friction, radiation of heat, cylinder condensation, and other losses, and must therefore be still further reduced in order to represent the actual or net efficiency given by the engine. These losses often amount to a large fraction of the total theoretical power of the engine. Assuming, therefore, that the theoretical efficiency of a given engine is 15 to 20 per cent, as calculated by the above formula, then the actual commercial efficiency will be in the neighborhood of 8 to 12 per cent. As a matter of fact, these figures are approximately the theoretical and actual efficiencies given by good steam-engines in ordinary practice. Another way to arrive at this same fact, and one which is more concrete, is to compare the actual consumption of coal per horse-power hour with the amount of coal that would be required if the entire energy were converted into mechanical work. The amount of heat-energy produced by the complete combustion of one pound of good coal is about 7,500 heat-units, which is equal to about 10,000,000 foot-pounds, which would give one horse-power for five hours; consequently the amount of coal required per horse-power hour is only .2 lb. The actual consumption of coal in a very good steam-engine is 2 lbs. per horse-power hour, and much more frequently 3 or 4 lbs., or even more; hence, the actual consumption of coal is ten to twenty times the theoretical amount which would be required if all the

heat were converted into mechanical power. The simple reason why the theoretical efficiency of a heat-engine is ordinarily far below 100 per cent, even without taking account of friction, etc., is the fact that a great deal of the heat-energy of the steam or gas passes out of the cylinder in the exhaust, and is not converted into mechanical energy. It is analogous to the case of a water-wheel which only utilizes a small fraction of the total fall or head of water. This fact is clearly shown by the formula given above, in which T_2 represents the temperature of the out-going steam or gas. If this temperature were absolute zero ($-273°$ C.), then the efficiency would be 100 per cent. If, on the other hand, the temperature T_2 is considerably above absolute zero, then the efficiency is correspondingly reduced below 100 per cent. As a matter of fact, the temperature of the exhaust of non-condensing engines is at least 100° C., or 373° absolute; and in the case of condensing engines, T_2 is about 300° to 325° absolute. Now, it would not seem to be possible to reduce these temperatures further, for the simple reason that a non-condensing engine cannot have a temperature in the exhaust below boiling-point; and the temperature of water for condensation cannot be below freezing, and is usually considerably above that point. The inference would therefore be that the only practical method of improving the efficiency of a heat-engine is to raise the initial temperature of the steam or gas. In point of fact, this is the way that the efficiency of heat-engines has been, and is now being, increased. In the time of James Watt, very low steam-pressures were employed, usually about 5 or 10 lbs. per square inch; and before that time even lower pressures, of 2 or 3 lbs., were employed. These low initial pressures, and therefore temperatures, necessarily meant low efficiency and large consumption of coal per horse-power hour. Since that time steam-pressures have been steadily increased, until we now have 150 or even 200 lbs. pressure on very fast passenger or war vessels. Indeed, the principal improvement in the steam-engine during the present century has been the increase of steam-pressure and the necessary strengthening and modification of the boilers and engines in order to stand these high pressures, which not only greatly augment the efficiency, but also produce much more power in the same size of engine.

Obviously great difficulties are encountered in largely increasing the pressure. In the case of the steam-boiler there are at least two serious obstacles, which are apparently inherent and almost insurmountable. The first of these is the fact that the thickness of the boiler, upon which its strength largely depends, cannot be very much increased without reducing the passage of heat through it, and without adding enormous weight and cost to the boiler, the surface required being large. There are also practical difficulties in the construction of a boiler of very thick metal. A still more serious difficulty is the fact that, as the pressure, and therefore temperature, of the steam are raised, a point is finally reached at which the strength of the boiler begins to be reduced by the heat, and would not permit further increase of pressure. The difficulty of lubrication at high temperatures is also a serious obstacle.

Gas-Engines. — In this respect the gas-engine apparently possesses great advantages over the steam-engine in its possible ultimate efficiency, for the reason that the high pressure and temperature are produced directly in the cylinder, which can be made of almost unlimited thickness, since it is comparatively small, and the heat does not have to be transmitted through its walls. In this way we entirely eliminate the steam-boiler, which is the chief limitation to the increase of steam-pressure. It cannot be said that the gas-engine has as yet realized much of this great advantage over the steam-engine. It is probably a fact, however, that there are gas-engines working to-day of which the theoretical and actual efficiencies are higher than those of the best steam-engines. Professor Unwin states in his lecture before the Society of Arts, January, 1893, that gas-engines have already given a thermal efficiency twice that of large steam-engines. Professor Ewing * has pointed out that the theoretical efficiency of the gas-engine would be 87 per cent if the initial temperature were that of combustion, and the final temperature that of the ordinary atmosphere. Previous compression of the gas would, of course, be necessary, and all friction and other losses would have to be eliminated. Assuming, however, that these losses amount to one-half of the theoretical power of the engine, an actual efficiency of 43½ per cent could still be obtained, which would be about four times the

* Article on "Steam Engine," *Ency. Brit.*, 1887.

net efficiency of the best steam-engines of the present day. The present gas-engines have several practical difficulties, and will have to be radically improved before very high efficiencies can be secured; but they seem to possess the possibility of efficiencies much greater than those of the steam-engine. To show that a very high efficiency is not entirely visionary, we can refer to the cannon, which is really a gas-engine, since it converts heat-energy into mechanical energy. Professor Thurston states that a cannon actually has a thermo-dynamic efficiency of about 50 per cent.*

The hot-air engine has been developed by Ericsson and others, and is both safe and convenient; but it is far inferior to the internal-combustion gas-engine in actual as well as theoretical efficiency and output.

The remarkable increase in economy which has been secured during the last few years by the use of compound, triple-expansion, and quadruple-expansion steam-engines for both marine and land work, might lead one to imagine that this improvement can be carried on almost indefinitely. As a matter of fact, however, compound engines are just as surely limited in their theoretical efficiency as the simple engine. Their efficiency depends upon the initial and final temperatures of the steam as expressed by the formula discussed above, just as truly as in the case of any other heat-engine. The greater economy of compound engines is largely due to the reduction of cylinder condensation by avoiding large ranges of temperature in any one cylinder. This simply means that the simple engine would have larger losses, and its actual efficiency would be much less, than the theoretical; whereas, in the case of a compound engine the actual efficiency would approximate more closely to the theoretical. Compound engines thus enable higher pressures to be used without having the great losses due to cylinder condensation which would occur in simple engines. It has been shown above, however, that apparently there are practical limits to the increase of the initial temperature; and it is a fact that even if the boiler could be kept at a red heat, the theoretical efficiency of the steam-engine would only be about 60 per cent, and the actual efficiency of course considerably lower.

The substitution of other fluids for water in boilers and engines

* *Science*, Oct. 31, 1891.

is fallacious, both scientifically and practically, and gives no hope of increased economy in the production of power. The same inexorable law of thermo-dynamics prevents the efficiency from being made higher, except by increasing the initial temperature or decreasing the final temperature. Bisulphide of carbon, ether, and other volatile fluids in place of water have been tried again and again by inventors, either from ignorance or intention to deceive. It is perfectly obvious, however, that the substitution of these liquids cannot help to secure a higher initial temperature; in fact, it would rather tend to increase the difficulty, and produce still more disastrous results in case of an explosion. To be sure, the final temperature of a non-condensing engine using ether instead of water would be 310° absolute instead of 373°; but this slight difference would be more than outweighed by the practical difficulties of using ether instead of water. In the case of a condensing engine the final temperature would be practically the same, whatever liquid might be employed in the boiler.

Direct Conversion of Fuel Energy. — The heat-engine, considered from all these points of view, does not seem to afford much encouragement for high efficiency in the conversion of fuel-energy into mechanical energy, except, perhaps, in the case of the gas-engine, which, however, still needs radical improvements. Moreover, in the generation of electrical energy the production of mechanical energy is merely a step, and the dynamo must be used to convert the mechanical into electrical energy; and although the electrical engineer can proudly say that the dynamo is the most efficient and the most perfect machine in existence, nevertheless our present method of producing electricity by means of a boiler, steam-engine, and dynamo is very indirect and complicated. The dream of the electrical engineer and scientist has therefore been to convert the energy of fuel directly into electrical energy, but as yet little or no practical progress has been made in this direction.

Thermo-electric Batteries. — It is possible to burn coal, gas, or other fuel, and use the heat produced, in a thermo-electric battery to generate electric currents directly. In simplicity this process is all that could be desired, since there is only one simple apparatus, without any moving parts, which is as harmless and easily taken care of as an ordinary stove, but unfortunately the

efficiency is very low; in fact, it is limited by the same law as the heat-engine, and is expressed by the same formula, $\frac{T_1 - T_2}{T_2}$, in which T_1 and T_2 are the temperatures of the ends of the elements. The possible differences of temperature between the ends would not seem to be so limited as the possible temperature of a steam-boiler. There are, however, many practical difficulties in maintaining one end of the elements at a very high temperature and the other end at a low temperature; and great trouble has been found in making perfect joints between dissimilar metals which would not crack after repeated heating and cooling.

Many persons think that there is an inherent deterioration of a thermo-electric battery which necessarily occurs after any considerable period of action. The author has made numerous experiments in connection with these batteries, and has seen some of them which have been in use several months almost continuously giving a fair output of .05 volt *external* potential difference, and 5 amperes per element ($1 \times 1 \times 4$ inches), without any apparent diminution in activity. There would seem to be no reason why there should be any such inevitable deterioration, beyond the fact that it is difficult to make a permanent joint between dissimilar metals, as already stated. This difficulty can be, in fact it has been, overcome by proper mechanical design and construction. The real difficulty is the low efficiency and small output of thermo-electric batteries. Probably the best results so far obtained do not give an efficiency over one or two per cent; that is, not more than one or two per cent of the heat-energy is converted into electrical energy, and probably the best output so far obtained is that stated above.

This efficiency is, of course, extremely low; but the simplicity and directness of the process would make up for a considerable sacrifice in efficiency, provided it is practical in other respects. The output is very small, but a comparison shows that a 25 horse-power plant, consisting of boiler, steam-engine, and dynamo, would occupy a space about 30×30 feet and 10 feet high; and a thermo-electric plant of the same generating power would occupy a room 20×20 feet and 10 feet high. In short, the thermo-electric battery is by no means utterly unpractical even at the present time, and it possesses great possibilities of future improve-

ment; and though it might not compete with the present method for large central stations, it is certainly admirably adapted to small isolated plants, where its simplicity, safety, and ease of attendance, would be of the greatest importance. The lower efficiency would be of small consequence compared with these other advantages. There are probably fewer serious difficulties in the case of thermo-electric batteries than in the case of secondary batteries; and the same amount of time, money, and scientific ability which have been expended on the latter would probably bring the former to a fair state of perfection, and would certainly make them applicable to a great many useful purposes.

The Thermo-magnetic or Pyro-magnetic Generator has been experimented upon by Edison and others. In 1887 Edison constructed both generators and motors of this kind.* The action of this form of electric generator depends upon the fact that iron or nickel loses almost all its power to conduct magnetism when heated to a certain temperature. If, therefore, a core of iron surrounded by a coil be connected to a magnet by means of thin strips of iron or nickel, a current is generated in the coil of wire when the strips are alternately heated and cooled, because the lines of force are first cut off, then allowed to pass, and so on. This machine has the same disadvantages as the thermo-electric battery, being low in efficiency, and requiring a large apparatus for a comparatively small output. Nickel has usually been employed instead of iron as the material to be alternately heated and cooled, for the reason that it loses its magnetic conductivity at a lower temperature than iron, this point being 310° C.; but nickel, of course, has considerably less permeability than iron, and therefore, although the required range of temperature is less, the amount of magnetism is also less. Furthermore, the second law of thermodynamics applies to this apparatus, as, in fact, it does to all apparatus for converting heat-energy into any other form of energy; therefore, to obtain a high efficiency, we must have a great range in temperature. Theoretically, it might therefore be better to employ iron instead of nickel, since its point of practical loss of permeability is 785° C.

* *Electrical World*, Aug. 27, 1887.

It should be observed that neither thermo-electric nor thermo-magnetic generators are true cases of the "direct conversion" of fuel energy into electricity. In both of them the energy is first converted into heat, which introduces a certain indirectness, and, what is more objectionable, brings the apparatus under the second law of thermo-dynamics, and thereby tends to make the efficiency very low, which is characteristic of all apparatus for converting heat-energy into any other form of energy.

Primary Batteries. — Numerous attempts have been made to accomplish the strictly direct conversion of fuel-energy into electricity, but none of them can be said to be at all practicable. Jablochkoff, in 1877, patented a voltaic battery in which carbon was used as the positive plate, the exciting-fluid being fused potassium nitrate. This battery is similar in principle to an ordinary Daniell battery, but the electric current is actually produced directly from the chemical energy of fuel, and the theoretical efficiency might be nearly 100 per cent; but, unfortunately, the active fluid, or depolarizer, in this battery is very expensive. Attempts have therefore been made by other inventors and experimenters to use some fused compound which could be reoxidized by passing air through it. For example, fused sodium manganate will act in that way; but it has practical difficulties.

It is possible that a cell of this kind might consist of a large metallic vessel forming the negative plate. This would be surrounded with asbestus or other material to preserve the heat. It could be coated inside with silver or nickel, to prevent action by the alkalies, etc., which might be present. This vessel should be filled with a fused compound capable of being reoxidized by the oxygen of the air which would be forced through it. The fuel could be supplied to the cell in the same way that coal is shoveled under a boiler, and would be kept in place and out of contact with the sides of the vessel by partitions of earthenware. The fuel would float on the surface of the fused compound, and connection might be made to it by means of bars of iron. Such a cell is by no means merely imaginary; it could actually be built and operated successfully. The practical trouble would be that the *E.M.F.* would be very low, only about one volt, and the internal resistance could not be made low enough to give a large out-

put of current with this low *E.M.F.* It necessitates, therefore, a large apparatus to generate even one horse-power. The low voltage would require a large number of cells to be used for most practical purposes, or else transformation by means of a dynamotor. There would be a tendency to an accumulation of impurities in the cell, brought there by the fuel, which would necessitate the renewal of the fused compound, and involve considerable expense. Other forms of voltaic battery might be employed for direct conversion, such, for example, as a gas-battery consisting of two plates of carbon, one of which is supplied with hydrogen or carbonic oxide produced by gasifying the fuel, and the other is fed with the oxygen of the air. Batteries of this sort have been tried; but it is difficult to supply the gases at the surfaces of the plates under the liquid, where it is necessary that the action should take place.

The ordinary primary battery is almost a case of direct conversion. Commercial zinc is produced by the chemical action of fuel (carbon) upon oxide of zinc. This zinc is used in a cell where it combines, usually with sulphuric acid to form sulphate of zinc. The energy of the combination is given out in the form of electric current. The author has elsewhere discussed primary batteries in detail, and given various data of *E.M.F.*, cost, etc., of different combinations.* These figures are not encouraging, even theoretically; and it is of course a well-known fact that this source of current is not at all satisfactory when any considerable amount of current is required.

The principal objections to primary batteries are high cost, large space occupied, and great trouble in maintenance. In the paper cited, it is shown that in the cheapest cell, the Bunsen, the cost of the theoretical amount of material required would be 20 cents per horse-power hour, to which must be added a considerable amount for waste material, and for labor in taking care of the battery, making a total cost of at least 30 cents per horse-power hour. This is over ten times as great as the cost of electric power generated by means of the engine and dynamo, and makes this source of energy entirely out of the question where anything more than a small fraction of a horse-

* "Possibilities and Limitations of Chemical Generators of Electricity," *Trans., Am. Inst. Elec. Eng.*, May, 1888. *The Electrical Engineer*, June, 1888.

power is needed. The zinc alone in a primary battery costs about 10 cents per horse-power hour; hence it would not help matters much if some depolarizer were discovered which would cost nothing. This shows the absurdity of the commonly advertised claims of a cheap depolarizer, with which a primary battery can supply "a large number of electric lights at a merely nominal cost."

The other common claim of a battery in which very little zinc is consumed is equally preposterous, since it is a well-known fact that at least 1.17 grams of zinc must be consumed per ampere hour. Hence we can calculate that if the *E.M.F.* were two volts, it would require almost exactly one pound of zinc per horse-power hour. This voltage is about as high as can be obtained in primary batteries; but even if twice this voltage could be obtained, which is practically impossible, it would still require ½ lb. of zinc per horse-power hour. The advantage of all these voltaic or chemical generators of electricity is that they are not limited by the second law of thermodynamics. They can therefore have a theoretical efficiency of nearly 100 per cent, and sometimes actually have a practical efficiency of over 90 per cent. In this respect they are much more hopeful than the apparatus in which heat-energy is converted into mechanical or electrical energy, but practically they are far inferior at present.

In conclusion, it can be said that a study of the possibilities of generating electricity very directly and cheaply is not particularly encouraging, and it would not seem that there is any great hope of a radical improvement in this direction in the near future. Apparently it will be necessary to content ourselves with the gradual but steady improvement of the means which we already have. It is possible, however, that some entirely new principle may be discovered by which electricity can be produced; but it cannot be said that there is any immediate prospect or indication of such a discovery, although there may be hundreds of investigators working directly or indirectly upon this fascinating problem in well-equipped laboratories, both collegiate and commercial. It would be very foolish, however, for any one to say that such discoveries are impossible, or even very unlikely. Certain facts may be cited which would indicate

not only the possibility, but the probability, of the existence of important undiscovered principles. It was pointed out about a century ago by that great American, Count Rumford, who possessed a knowledge of these very subjects far ahead of his time, that the efficiency of an animal is greater than that of a steam-engine; that is to say, a certain amount of hay fed to a horse would enable him to perform more actual mechanical work than could be obtained from the same amount of hay burned under the boiler of a steam-engine. This simply means that the energy contained in food is converted into mechanical work by the natural processes acting in the organs and muscles of an animal with a higher efficiency than can be obtained by the methods now used by man in the artificial production of power.

This is analogous to the fact that the glowworm produces light with very much higher efficiency than any artificial method. Professor Langley has shown that an ordinary gas-burner emits 400 times as much heat as a glowworm when they both give exactly the same amount of light. In other words, nearly all of the energy given out by a gas-burner is invisible heat, which contributes nothing to the lighting effect; whereas, in the case of the glowworm, a large part of the energy emitted is in the luminous part of the spectrum. These facts concerning the very much higher efficiency of animals in the production of either mechanical work or light might encourage us to hope that these very processes, or similar ones, may be discovered and used artificially. The production by ordinary chemical processes of organic substances such as quinine, alizarine, and many others, which was formerly thought impossible, demonstrates that the processes of nature can be imitated by man in the arts.

It would thus appear that the only hope of the cheaper generation of electricity lies in two directions, one being the gradual improvement of the present processes, which will doubtless continue to go on slowly but surely. The development of the gas-engine, steam-turbine and the Tesla steam-oscillator may considerably increase the efficiency of electrical generation, but they would be subject to many of the limitations of heat-engines. The other hope is the discovery of some radically new method by which electricity can be gotten directly from fuel-energy. But this hope is

very indefinite at present, and may be realized in one year, or perhaps not for a hundred, or even a thousand, years. The work of Tesla and others with high-frequency alternating currents and electrical discharges gives hope of the more efficient production of light from electricity; but even in that case it would still be necessary to generate electricity by practically the same means as at present.

CHAPTER VIII.

THE STEAM-ENGINE, HISTORY AND GENERAL PRINCIPLES.

Introduction. — A general study and comparison of the various methods of generating electricity have already been given in the last chapter, including the principles of the conversion of heat into mechanical energy by means of steam and other heat engines. In taking up the special consideration of the steam-engine, it will be interesting and profitable to briefly review the history of the machine which has been such an important factor in modern civilization, not only because of its general applications, but also because it is an indispensable element in the ordinary method now employed to generate electricity.

Historical Notes. — The starting-point in the history of the steam-engine is always stated to be the simple rotary engine devised by Hero of Alexandria about two thousand years ago. This engine, a steam-fountain, and his many other steam-apparatus, were only toys, however, and were never applied to any useful purpose. The next great step was made by the Marquis of Worcester, who built a steam-engine which was an actual working-machine of considerable size and power. The exact date when this machine was made is not known, but it was probably about 1628.* He published a very obscure description of it in the *Century of Inventions* in 1663. The facts in regard to this remarkable machine are shrouded in considerable doubt and mystery, probably because of the actual danger of persecution to which any one exposed himself in those early days by bringing out any invention, particularly such a radical one as the steam-engine. It appears that the engine contained the important improvement of a separate boiler, and, in fact, possessed many features that showed the remarkable genius of its inventor.

Thomas Savery, in 1698, obtained a patent for a water-raising apparatus, which was the first real attempt to use a steam-engine *commercially*. This engine acted merely by the pressure of steam

* Thurston, *Growth of the Steam Engine.*

upon the surface of the water in two chambers acting alternately, and did not contain any piston or cylinder. Denis Papin had previous to this time (1690) described a cylinder and piston engine, and had even suggested the utilization of the condensing-power of steam; but the form described had the radical defect of using one and the same vessel for boiler, cylinder, and condenser. He afterwards (1705) went back to some of Savery's ideas. Newcomen, in 1705, was the first to use a cylinder and piston and a separate boiler; but the engine still had the defect of having the condensation of the steam performed in the cylinder. It was far more practicable, however, than anything which had preceded it, and began to be used regularly for pumping water out of mines as early as 1711. These Newcomen engines required the steam to be let into and out of the cylinder through valves which had to be worked by hand. In 1713 Humphrey Potter, an ingenious boy employed to operate the valves of one of these engines, connected the valves to a moving part of the engine by cords in such a way as to cause them to work automatically, in order to save himself the trouble of attending to them. This very important invention was improved by Henry Beighton in 1718.

These improved Newcomen engines were used regularly for pumping mines until Watt made a series of brilliant inventions, which were so important and radical that he is ordinarily said to be the inventor of the steam-engine. The most valuable improvement due to Watt is the use of a condenser separate from the cylinder of the engine, which is, indeed, absolutely essential in order to avoid the enormous waste which would result from condensing the steam in the cylinder itself. This invention was made in 1765, and patented in 1769. Watt, in 1782, also patented the double-action principle, or use of steam on both sides of the piston; also the use of steam *expansively*, — that is, the introduction of a certain amount of steam into the cylinder, which does work upon the piston by expanding after the connection with the boiler has been shut off. Both of these inventions were made several years before they were patented. Besides these fundamental principles contributed by Watt, he also greatly perfected the general design and details of the mechanical construction. In fact, his work was so complete that the simple condensing engine of to-day is practically identical with the engine of Watt.

The only great improvement in the steam-engine since the inventions of Watt is the compound or multiple expansion engine patented by Hornblower in 1781, and revived by Woolf in 1804, and even this had been conceived by Watt.

The history of the *theory* of the steam-engine, and the science of thermo-dynamics upon which it is based, may be considered to have started when Carnot, in 1824, first showed how to treat the *cyclic* action of any heat-engine by considering each cycle separately. The use of this method in the study of heat, as well as in electricity, magnetism, and other sciences, is of the greatest value, and seems to be the best possible way to secure definiteness and completeness in scientific analysis. The use of this method in studying magnetic and electrostatic hysteresis, by Ewing and others, has greatly added to the clearness and advancement of these branches of science. The determination of the mechanical equivalent of heat by Joule in 1843 (which, in fact, is the most essential element in the establishment of the principle of conservation of energy) gave the real foundation to the science of heat, and, in fact, of all modern science. From 1849 onward, the science of thermo-dynamics was rapidly developed by Clausius, Rankine, and Thomson. The publication of Rankine's classical work on the steam-engine, in 1859, gave the almost complete application of pure thermo-dynamics to the practical case of the steam-engine, and established that intimate relation between theory and practice which is so essential to the proper and rapid development of both.

The recent history of the steam-engine is made up of the development of the compound and triple expansion types, improvements in the mechanism for governing speed, the perfection of the design and construction of the various parts and details, and the devising of suitable forms of engine for special work.

It happens that all of these modern improvements are of particular importance in connection with electric lighting; in fact, they are largely the direct result of progress in the use of electric light and power.

THE PRINCIPLES OF THE STEAM-ENGINE.

A complete study of the steam-engine requires a thorough knowledge of the science of heat, and its relation to mechanics, — thermo-dynamics, — and would occupy far more space than can

be devoted to it in this treatise; but certain fundamental principles are sufficient to enable one to understand the steam-engine well enough for those who are not specialists in the subject.

The two laws upon which the entire science of heat is based, called the first and second laws of thermo-dynamics, are:—

1. *The law of the equivalence of heat and mechanical energy,* which may be stated as follows: *A given quantity of mechanical energy is always equivalent to, and can be converted into, a certain definite quantity of heat;* or, to take a concrete case, 1 heat-unit, that is, the heat required to raise 1 gram of water 1° C., is exactly equal to the mechanical work required to raise 1 gram 428 meters high; or, in the English system, 1 lb. of water heated 1° F., is equivalent to 772 foot-lbs. according to Joule, or 780 according to the latest results (page 21).

The second law of thermo-dynamics is very differently stated by different authorities, and none of them are very easily understood, the statement of Rankine in particular being quite abstruse. The corollary of this law, which has practically the same significance, and is in much better form to be understood and used in connection with heat-engines, is that given on page 76, and expressed by the formula: Efficiency $= \frac{T_1 - T_2}{T_1}$. The meaning of this expression is that *the highest possible efficiency of any heat-engine is equal to the difference in temperatures between which it works divided by the initial absolute temperature.*

In any heat-engine there is the working substance, the changes in temperature of which give the action of the engine. In practice this substance is either water-vapor (steam), gas, or air, and is called the fluid. There are two important laws giving the relations between the temperature, pressure, and volume of a gas:—

1. The law of Boyle or Mariotte, which states that the volume of a gas is inversely proportional to the pressure, the temperature being kept constant; that is, $p\,v = C$, in which p and v are the pressure and volume respectively, and C is a constant depending upon the density and other properties of the gas.

2. The law of Charles or Gay Lussac, which states that a gas increases $\frac{1}{273}$ of its volume at 0° C. for each degree of rise in temperature; that is, $v_t = v_o \left(1 + \frac{t}{273}\right)$, in which v_t is the

volume at any given temperature, t in centigrade degrees, and v_0 is the volume at zero. The combined expression for these two laws is $p v = R\ (t + 273)$. Now, since $t + 273$ is the absolute temperature, T, we have $p v = RT$.

The above laws apply, however, only to a perfect gas, such as air, or any other permanent gas; hence they can be used in discussing gas and hot-air engines, but they have to be considerably modified in order to apply them to the case of steam or other vapor, the action of which is quite different from that of a perfect gas. The properties of steam, and the relations between its pressure, volume, and temperature, are usually given in the form of a table similar to the one printed below. The figures are for steam, which is neither superheated nor supersaturated (i.e., "wet"). The data for either of these latter kinds of steam are somewhat different, depending upon the degree of superheating or supersaturation.

Table of the Properties of Saturated Steam.

Absolute Pressure. Lbs. per Sq. In. above Vacuum.	Temperature, Fahrenheit.	Total Heat of Evap. from 32°.	Density. (Weight of Cu. Ft. in Lbs.)	Volume of 1 Lb. in Cu. Ft.
1	102	1113.1	.00303	330.4
5	162.4	1131.5	.01378	72.56
10	193.3	1140.9	.02644	37.83
14.7	212	1146.6	.03793	26.37
20	228	1151.5	.0507	19.73
30	250.3	1158.3	.0742	13.48
40	267.2	1163.4	.09723	10.28
50	280.9	1167.6	.11993	8.34
60	292.6	1171.2	.14236	7.024
70	302.8	1174.3	.16458	6.076
80	311.9	1177.1	.18663	5.358
90	320.1	1179.6	.20853	4.796
100	327.6	1181.9	.2303	4.342
110	334.6	1184	.2519	3.97
120	341.1	1186	.2735	3.66
130	347.1	1187.8	.295	3.39
140	352.8	1189.6	.3163	3.16
150	358.2	1191.2	.338	2.96
175	370.5	1195	.390	2.56
200	381.6	1198.3	.443	2.26
250	400.9	1204.2	.548	1.83
300	417.4	1209.2	.652	1.54
400	445	1217.7	.857	1.17
500	467.4	1224.5	1.062	.94

This is taken from Thurston's *Manual of the Steam Engine*, Part I., page 820, which contains complete tables of the data of steam. The pressure above that of the atmosphere, as shown

by an ordinary gauge, is 14.7 lbs. less than the figure in the first column.

The action in the cylinder of an engine can be determined analytically by applying the principles stated above. If a certain volume of gas expands *isothermally* (i. e., its temperature is kept constant), the pressure varies inversely with the volume, since, by hypothesis, T is constant in the equation $pv = RT$, on page 92; hence, $pv = \text{const.}$

The external work performed by the gas in expanding from the volume v_1 to v_2 is —

$$W = \int_{v_1}^{v_2} p dv = RT \int_{v_1}^{v_2} \frac{dv}{v} = RT \log \frac{v_2}{v_1} = RT \log \frac{p_1}{p_2}$$

To keep the temperature constant, the gas must be supplied with an amount of heat mechanically equivalent to this work.

If the expansion is *adiabatic*, i. e., the gas neither receives nor gives out heat, the external work performed is by the energy of the gas, and the pressure falls more rapidly than by isothermal expansion, the relation being $pv^k = p_1 v_1^k = \text{const.}$, in which k is the ratio of the specific heats $= 1.41$. The corresponding temperatures are —

$$\frac{T}{T_1} = \left(\frac{p}{p_1}\right)^{\frac{k-1}{k}} = \left(\frac{p}{p_1}\right)^{.29} = \left(\frac{v_1}{v}\right)^{k-1} = \left(\frac{v_1}{v}\right)^{.41}.$$

The external work during adiabatic expansion from v_1 to v_2 is —

$$W = \int_{v_1}^{v_2} p dv = p_1 v_1^k \int_{v_1}^{v_2} \frac{dv}{v^k} = \frac{p_1 v_1^{1.41}}{.41} \left(\frac{1}{v_1^{.41}} - \frac{1}{v_2^{.41}}\right) = \frac{R}{.41}(T_1 - T_2).$$

Theoretically, gas should expand adiabatically in an engine, but in practice some of its heat is given up to the cylinder; hence the temperature and pressure resulting from a certain increase in volume are somewhat less than those found by the above formulæ. The adiabatic curve for saturated steam, given by Rankine, is, $pv^{\frac{10}{9}} = \text{const.}$; which approximates actual results, but is merely empirical, and depends upon the dryness of the steam, etc.

The practical method is to determine directly, by means of a steam-engine indicator, the curve (Fig. 26) representing the actual variations of the pressure in the cylinder throughout a cycle (forward and back stroke). The area of this indicator diagram found by a planimeter, gives the work done by the steam on the piston during that cycle, whatever the law of expansion.

CHAPTER IX.

STEAM-BOILERS FOR ELECTRIC LIGHTING.

A STEAM-BOILER is a vessel in which water is evaporated by heat produced by the combustion of fuel, the resulting steam being used in a steam-engine for the generation of mechanical power. Boilers are made of wrought-iron or mild steel, and with careful limitations, cast iron is used for certain parts. The form and construction of boilers depend upon the purpose for which they are to be used, the character of fuel employed, and other circumstances. The kinds of fuel available for steam-boilers, and the data concerning each, are given in the following table: —

FUEL.	SPECIFIC GRAVITY. Average.	AIR REQUIRED per Lb. of Fuel. Twice the Theoretical.	TEMPERATURE OF COMBUSTION with Twice the Theoretical Supply of Air.	HEATING-POWER PER POUND.		
				In Heat-Units Lb.-Cent.	Theoretical Amount of Water evap. at 100° C.	Practical Amount of Water evap. in boiler.
Petroleum —						
Crude . .	.88	31 lbs.	1500° C.	11500	21.3	14 to 16 lbs.
Coal —						
Anthracite .	1.45	24	1400	7500	14	8 to 10 lbs.
Bituminous.	1.3	25	1425	8000	14.8	8 to 10 lbs.
Coke . . .	.75	24	1400	7500	14	8 to 10 lbs.
Wood (Hard) —						
Kiln dried .	.5 to .9	12	1200	3800	7	4 to 5 lbs.
Air dried .	.6 to 1	9.8	1100	2900	5.4	3 to 4 lbs.

In calculating the weight or volume of air required for combustion, the following data are useful: —

One pound of air at ordinary barometric pressure, and at 15° C. (59° F.), is almost exactly 13 cubic feet, and contains .23 lb. of oxygen. The volume, V_t, at any other temperature, by Gay Lussac's law (page 91), is, $V_t = \frac{273+t}{273+15} \times 13 = \frac{13}{288}(273+t)$, in which t is the temperature centigrade. The volume, V_p, at any given pressure is, $V_p = \frac{14.7}{P} V_t$, in which P is the pressure in pounds per square inch above vacuum, and V_t is the volume at the given temperature, as found by the preceding formula.

The heat of combustion of a fuel may be calculated approximately by the formula:*—

Heat in centigrade units $= 8140\,C+34500\,H-3000(O+N)$.

Heat in Fahrenheit units $=14650\,C+62100\,H-5400(O+N)$.

In these equations the letters C, H, O, and N represent the weights of carbon, hydrogen, oxygen, and nitrogen (exclusive of ash and moisture) in the fuel.

The air required for combustion may be calculated approximately by the formula, weight of air $= 11.5\,C+34\,(H-\frac{1}{8}\,O)$, in which C, H, and O are the weights of carbon, hydrogen, and oxygen respectively. This weight of air is the theoretical amount, however, and should be increased from fifty to one hundred per cent to obtain complete combustion.

The use of a poor quality of coal on account of cheapness is usually bad economy, as the percentage of ash is much larger, so that the cost of the combustible part of the fuel may be as great in cheap as in more expensive coal. Another disadvantage of cheap coal is the fact that a given boiler will not produce so much steam with it, consequently it takes a larger boiler, or a greater number, to produce the same amount of steam, which would add to the first cost as well as to the interest and depreciation on the plant. The trouble and expense of firing the boilers, handling ashes, etc., are also greater with poor coal.

Bituminous coal is more generally employed for steam generation throughout the world than anthracite; but in certain localities the latter is used exclusively, as, for example, in New York City, where the burning of the former is practically prohibited by the Board of Health. The engineer should always study carefully the local conditions of coal supply.

Wood as a fuel for boilers is quite common in localities where it is very cheap, being sometimes much cheaper than coal; as, for example, in Maine, Oregon, Washington, and other States where large forests still exist. The various kinds of wood, when dry, have practically the same evaporative value *per pound*. This is usually estimated at .4 the value of the same weight of coal. Wood is a fairly good fuel for boilers, where it is available and sufficiently cheap. Sawdust can be utilized as fuel for boilers, but a special furnace and automatic feeding-devices are

* "Notes on Steam Boilers," by Peabody & Miller, Boston, 1894.

required. Even spent tan-bark is sometimes employed, usually mixed with coal. Bagasse, the refuse of sugar-cane, is largely used as fuel in Cuba.

Petroleum, which is practically the only natural liquid fuel, has been largely used for boilers, and in many respects it has great advantages. The dust, dirt, smoke, ashes, and labor incidental to the use of coal are almost entirely avoided by employing petroleum. Some special form of burner is required, in which the oil is reduced to a fine spray by means of a steam or air jet. Great claims have been made concerning the economy of petroleum as fuel, but it is a question whether the actual results entirely justify the claims.* The chief practical difficulty in the use of petroleum is the fact that the heat is not widely or uniformly distributed, being very intense at certain points where it is liable to injure the boiler. The heat-units produced by petroleum when completely burned are about 50 per cent greater than from the same weight of coal; but, owing to the fact that it can be burned more perfectly, it has been found by experiments in this country, and also in Russia, that 1 lb. of petroleum is equal to 1.8 to 2 lbs. of coal. A gallon (U. S.) of petroleum weighs about 6.5 lbs., and is therefore equivalent under a boiler to about 11 to 13 lbs. of coal; and about 180 gallons are equal to a gross ton (2,240 lbs.) of coal, or about 160 gallons to one ton of 2,000 lbs. At the oil-wells, petroleum is worth about 2 to 3 cents per gallon, or .84 to $1.26 per barrel of 42 gallons, which is equivalent to $3.60 to $5.40 per ton for coal. The lowest price at which oil can be delivered in the vicinity of New York is about 3 to 4 cents per gallon, making it cost the same as coal at $5.40 to $7.20 per ton, which is nearly twice as much as the actual cost of coal in New York. Hence it would not seem to be cheaper than coal, even allowing for its more perfect combustion. The steam used to convert the oil into spray, or "dust," consumes considerable power, which is often forgotten in determining the cost of petroleum as fuel. Petroleum was employed exclusively, on account of its convenience and cleanliness, as fuel in the enormous plant of boilers at the Chicago Exposition of 1893.† The boilers there

* "Committee Report to American Street Railway Association, October, 1893," by E. G. Connette, chairman. *Electrical Engineer* (N.Y.), Oct. 25, 1893, p. 365.

† *Scientific American*, July 8, 1893.

heated by oil aggregated 20,500 horse-power, and it is stated that 1 lb. of oil evaporated 15 lbs. of water in that case.

Natural gas as a fuel possesses the advantages of cleanliness and convenience to an even greater extent than oil. In fact, it is almost ideal in these respects, and has been used extensively in districts where it is available. The disadvantages are uncertainty as to the continuance of the supply, intense localization of heat, similar to that produced by oil, and danger of explosion. In some cases the supply of gas has actually ceased; and it is a fact that quite a number of explosions have occurred, with serious results, due to the use of natural gas. The heating-power of natural gas is usually about 2 to 2.5 times that of the same weight of coal, or about 30,000 cubic feet are equivalent to a ton of coal.

Solid or liquid fuel can be converted into gas by means of a gas-producer or other similar apparatus. In some forms of producer the carbon of the coal is converted into carbon monoxide by partial combustion; the resulting gas is conveyed to the boiler, where it is completely burned to carbon dioxide. This method has the disadvantage of losing a considerable fraction of the heat in the first operation, and the resulting gas is considerably diluted with nitrogen. Another process of gasifying fuel is to convert it into water-gas, by treating it at a high temperature with steam, which is decomposed, hydrogen and carbon monoxide being formed, both of which are highly combustible. The reaction in this case is $C + H_2O = CO + H_2$. Petroleum may be gasified by passing it through very hot pipes, thus "cracking" it up into gaseous compounds, or by treating it with steam at a high temperature, thereby forming water-gas. But, as stated above, it is commonly used in the form of a spray, or "dust," obtained by the action of a steam- or air-jet.

The gas produced from solid or liquid fuel can be used under the boiler in a manner similar to natural gas, the advantages being the cleanliness and convenience obtained in the boiler-room; but it is obvious that there must be an apparatus for gasifying the fuel, so that this method has no great advantage over the direct use of coal under the boiler. This matter is considered further in connection with gas-engines.

Artificial fuel is sometimes used, consisting of various mixtures of coal-dust, or slack and other materials, with tar, pitch, or

equivalent material, to hold the particles together. It is usually pressed and baked in the form of blocks. These are commonly called "patent fuels." Their heating-power is about equal to that of the same weight of coal, but they are apt to have more ash. It is sometimes kept as a reserve supply in stations, where the square form enables it to be conveniently and compactly piled away in any available space.

Construction of Boilers. — The materials chiefly used in the construction of boilers are wrought iron or mild steel. The tensile strength of the former ranges from 40,000 to 60,000 lbs. per square inch. Professor Unwin * gives the average tenacity of iron plates as 46,000 lbs. per square inch, and steel plates 62,000

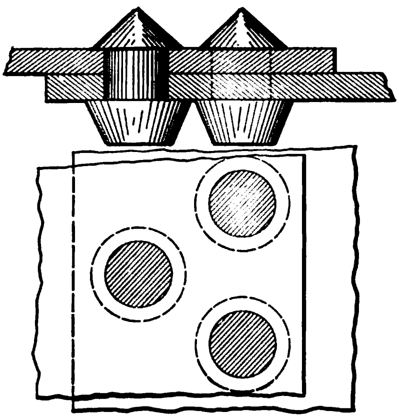


Fig. 11. Double-riveted Lap-Joint.

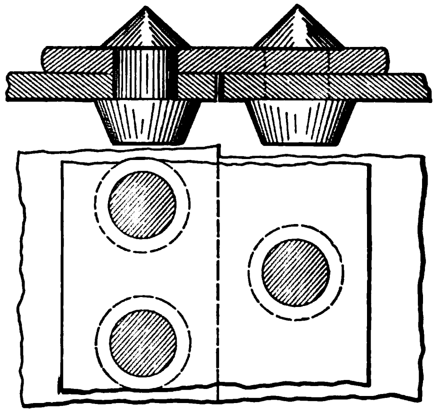


Fig. 12. Single-riveted Butt-Joint.

lbs. Cast iron is also used for certain parts of some types of boilers, but it is liable to crack, and its tensile strength is not nearly as much as that of wrought iron, being only about 15,000 to 25,000 lbs. per square inch; and even these figures cannot be relied upon, the modern practice being to eliminate cast iron entirely in parts of the boiler proper.

Boiler-shells are built up of sheets of wrought iron or wrought steel riveted together. Rivet-joints may either be lap-joints, as shown in Fig. 11, or butt-joints, Fig. 12, either of which may be single riveted or double riveted; and in high-pressure boilers the butt-joint has straps on both sides. The strength of riveted

* *Elements of Machine Design*, 1891, p. 112.

joints determines more than any other factor the safety of boilers, and they depend upon the following facts:—

1. The strength of the plate to resist being torn along the center line of a row of rivet-holes.

2. The resistance of the rivets against shearing.

3. The strength of the rivet or of the plate around the rivet to withstand crushing.

4. The resistance of the plate against being torn between the rivet-holes and the edge of the plate.

5. Friction between the plates, due to the force with which they are held together by the rivet. This last, however, should not be relied upon.

Before taking up the detailed study of the various forms of boiler, it will be well to consider the requirements of a perfect steam-boiler, which are many and difficult to obtain. These are as follows: The best material obtainable, and the highest grade of mechanical design and workmanship; freedom from danger of explosion; economy in the use of fuel, and cost of maintenance; considerable storage capacity for steam and water; constant and free circulation of water; a large surface for the disengagement of steam in order to avoid "priming," i.e., foaming; all parts readily accessible for cleaning and repairs; complete combustion of the fuel should take place before the gases escape to the chimney; joints and other weak parts should be removed as much as possible from the direct action of the fire; heating-surfaces should be of sufficient extent, and formed or arranged so as to extract as much of the heat as possible from the gases; the repairs required should be a minimum, since these cause great trouble and expense.

In addition to the above general requirements of steam-boilers, there are certain special requirements for each particular use to which they may be applied. In electric lighting, the special quality which a boiler should possess is ability to maintain a constant pressure; and it is particularly important that the pressure should not fall at full load. This quality is obviously desirable in almost any case; but it is of peculiar and vital importance in electric lighting, because the slightest variation in speed is objectionable, a change of even a small fraction of one per cent in voltage producing a perceptible fluctuation

in the light of an incandescent lamp. It might be said that the engine ought to govern for variations in steam-pressure; that is, maintain a constant speed irrespective of small changes in pressure. To a great extent such is the case; but when there are a large number of lamps in use, the load on the engine and dynamo and the loss of potential on the conductors being at a maximum, a decrease in steam-pressure would certainly tend to aggravate the difficulty. In stating that a boiler for electric lighting should give a constant pressure, it is not intended to imply that a boiler is necessarily always run at any particular pressure. It is a common practice to use lower steam-pressures for light loads and higher pressures for heavy loads; but in any case the boiler should *maintain* the given pressure. Another special requirement which a boiler for electric lighting should fulfill, is the ability to take care of wide variations in the load, which often occur in electric lighting. These variations are rarely rapid, however, and in this respect differ radically from the enormous and sudden fluctuations in load which occur in electric railway work. Two radically different methods may be adopted to provide for the large but comparatively slow changes in load which occur in electric lighting.

The first of these consists simply in employing boilers of the so-called "quick-steaming" type; that is, boilers with large heating-surface and comparatively small water capacity, which can be quickly brought into condition for use. This plan is largely followed, and water-tube boilers which are particularly quick-steaming are in use in most of the important central stations of the large cities of both Europe and America. The other method, which is almost diametrically opposite to the first, is that of "thermal storage," proposed by Mr. Druitt Halpin, and advocated by Professor W. C. Unwin* and Professor George Forbes.† The scheme consists in using boilers having only a capacity sufficient for the *average* load, these being run continuously day and night. At times of light load the steam is carried through pipes to large iron reservoirs of cheap construction, in which it heats a large quantity of water to a

* *Lecture before the Society of Arts*, London, January, 1893.

† Paper on "Thermal Storage for Central Stations," before Nat. Elec. Light Assoc., March 1, 1893. *Elec. World*, March 11, 1893.

high temperature. When the heavy demand for light arises in the evening, steam is drawn from these reservoirs. The losses of heat by radiation from the reservoirs can be made small by covering them with non-conducting material. Mr. Halpin claims that he can replace 22 boilers, working in the ordinary way, by 5 boilers and 92 of his storage cylinders, which are cheap to construct, and have a much smaller depreciation than the boilers. The advantages of the thermal-storage system would be that the wear and tear and waste of fuel involved in firing up a number of boilers for a few hours' work is avoided. The objection to the plan is that it is peculiar, involves the use of two different kinds of apparatus, and has not been tried sufficiently to demonstrate that it will work successfully in actual practice.

The various kinds of boilers may be classified as follows: —

STEAM-BOILERS.

CLASSES.	TYPES.
1. Plain cylinder boilers.	"Egg-ended" type.
2. Flue boilers.	Cornish type, single flue. Lancashire type, two flues. Galloway type, "breeches" flue.
3. Multitubular or "fire-tube" boilers.	Cylindrical tubular boiler. Locomotive boiler. Marine boiler.
4. Water-tube or "sectional" boilers.	Babcock and Wilcox and many other types.
5. Coil boilers.	Torpedo boat and other types.
6. Vertical boilers.	Various types which are usually modified forms of horizontal boilers.

Many of these types are not used to any great extent in electric lighting, and it is therefore not necessary to consider them. The forms of boiler commonly employed in electric lighting are: The water-tube boiler, the internally fired direct fire-tube marine boiler, the locomotive type of boiler, and the plain horizontal tubular boiler. It has already been stated that water-tube boilers of the Babcock & Wilcox and other types are very extensively used in electric lighting. They possess the advantages of being quick-steaming, not liable to disastrous explosions, and easily repaired and transported in sections. But the objections to them are that they are rather expensive, and do not have much capacity for water or steam, and cannot, therefore, stand

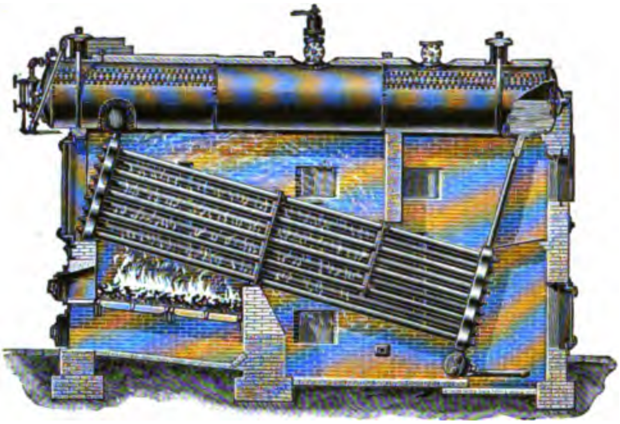


Fig. 13. Babcock & Wilcox's Sectional or Water-Tube Boiler.

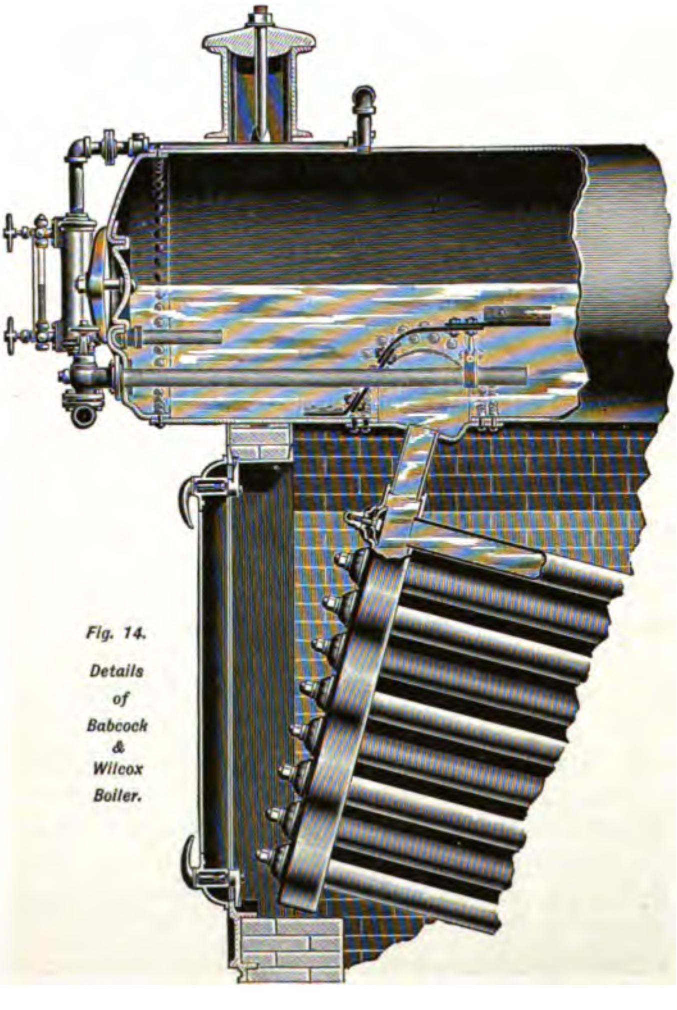


Fig. 14. Details of Babcock & Wilcox Boiler.

Fig. 15.

violent fluctuations of load, which, however, are not likely to occur in electric lighting.

The Babcock & Wilcox water-tube boiler, shown in Figs. 13, 14, and 15 is very generally used for electric lighting and other purposes in this country and many foreign countries. This and other similar types of boiler consist of a large number of parallel iron tubes joined at their ends by "headers," or connecting pieces of cast or wrought iron. The latter form is shown in Fig. 15, being required in high-pressure boilers. These tubes are ordinarily four inches in diameter, and are placed at a distance apart

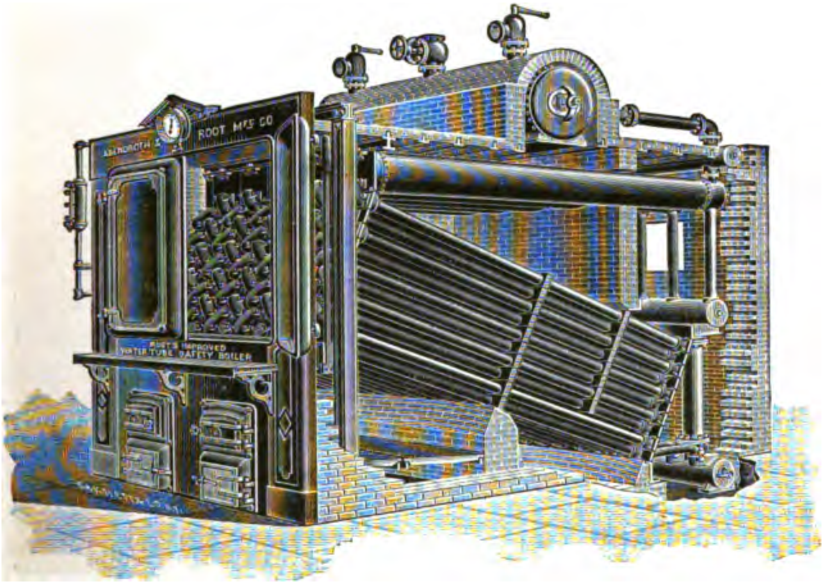


Fig. 16 a. Root Water-Tube Boiler.

about equal to their diameter. The tubes are "staggered," or arranged so that each tube is immediately over the space between two tubes in the row below. This has the effect of thoroughly abstracting the heat from the products of combustion. The mass of tubes are connected at both ends to the long horizontal steam and water drum above, the water-level being kept at such a height that this drum is about half full, as shown. At the rear the tubes are connected to the mud-drum below, into which the dirt, scale, etc., settles.

The path of the products of combustion is shown in Fig. 13.

They first pass directly upward from the grate, through all the water-tubes, being obliged to take this path by the bridge-wall at the back of the fire-box and a baffle-plate or partition which

Fig. 16 b. Sterling Water-Tube Boiler.

surrounds the tubes, and forms an extension of the bridge-wall. About half-way between this wall and the rear end of the tubes is another baffle-plate, above which is a hanging wall of brick. These, together, cause the gases to pass downward through the tubes, and finally upward again at the back, thus flowing three times through the entire mass of tubes.

The circulation of the water is also very effective in these types of boiler. The inclined position of the tubes causes the heated water to flow from the rear toward the front of the boiler, thus traveling in a direction opposite to that of the gases. In this way the water is acted upon by hotter gases the higher its own temperature becomes.

There are many other well-known types of water-tube boilers which are similar in principle but differ considerably in details of construction. Among these may be mentioned the Root, (Fig. 16 *a*) National, Heine, and Sterling.

In Europe the Steinmuller and other forms of water-tube boiler are used in addition to the Babcock & Wilcox, which latter is as widely used there as in America. All these types of

water-tube boilers are employed in electric lighting; in fact, it is one of their most important applications.

Cylindrical or Horizontal-Tubular Boilers. — A typical form is shown in Fig. 17, and consists of a cylindrical *shell*, closed at the ends by two flat *tube-plates*, through which the *fire-tubes* extend from one end to the other. The diameter of the fire-tubes is usually about 3 or 4 inches. Nearly two-thirds of the volume of the boiler is filled with water, the remaining space being reserved for the steam. The water-level is 6 to 8 inches above the top row of tubes. The tubes act as *stays* for the tube-plates below the water-line; but above the water-level the flat plates must be stayed by *through rods* from one plate to the other, or by diagonal stays to the shell of the boiler.

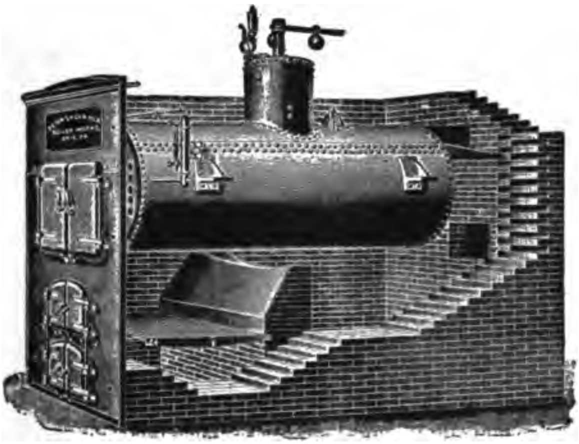


Fig. 17. Horizontal-Tubular Boiler.

The grate is under the *front end* of the boiler, and the products of combustion pass back under the boiler. A *bridge-wall* at the rear end of the grate is arranged to throw the gases into contact with the boiler. The gases return through the tubes, and pass out by the *up-take*, or flue leading to the chimney. The boiler is supported by cast-iron brackets, which are riveted to the shell, and rest on the side walls. A vertical *steam-dome* projects from the top of the boiler from which the steam is drawn. These boilers are made in sizes from about 3 feet in diameter and 7 feet long, having 12 horse-power capacity, to 7 feet in diameter and 20 feet long, having 200 horse-power capacity.

This assumes about 15 square feet of heating-surface per horse-power which is a safe rating for this type of boiler.

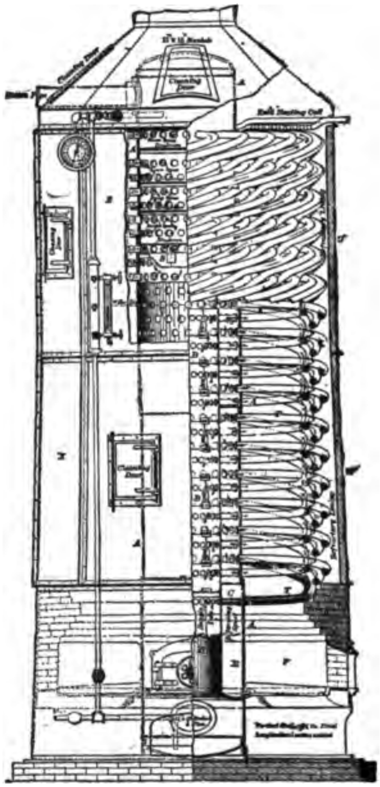


Fig. 18 a. "Climax" Vertical Boiler.

The Locomotive Boiler differs from the cylindrical-tubular in the fact that a rectangular *fire-box* is formed on the front of the boiler, and the products of combustion pass directly from the fire-box through the tubes to the end of the boiler, and out to the smoke-stack. Thus the gases make only one passage, whereas they pass forward again in the cylindrical-tubular boiler, which is therefore often called "return-tubular."

The "Climax" Vertical Steam-Boiler.—The construction of this boiler is shown in Fig. 18 *a*. The principal heating-surface is made up of the loop-like tubes *T*, which are expanded into the cylindrical shell *A*, two of them being shown blackened in the horizontal section (Fig. 18 *b*). Within the shell *A* is a second cylinder, *B*, which is not necessarily steam or water tight, and is bolted together in short sections for convenience of removal in case of repairs. The cylinder *B* is closed at the bottom and open at the top, which is a little below the water-level. The lower end of each tube *T* is connected to the inner cylinder *B* by means of a short tube *C*. These short tubes are not expanded, as it is not required that they should be tight. This arrangement is for the purpose of keeping up a rapid and constant circulation of water in the tubes *T*. The fire-box *V* surrounds the cylinder *A*, and the hot gases must pass

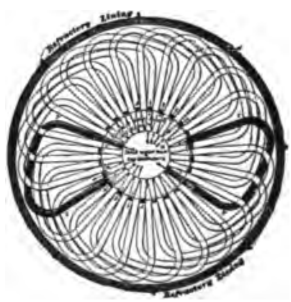


Fig. 18 b.

around all of the tubes on their way to the chimney. With a stationary grate several firing-doors are required for feeding coal on all sides; but a rotary grate is sometimes employed with this boiler, in which case only one fire-door is necessary.

Boiler-Setting. — Manufacturers of boilers usually have plans for setting which are specially adapted to each particular type; and it is well to follow these as closely as possible, in order to get the best results from a given boiler. Fig. 17 shows a setting for the ordinary horizontal tubular boiler. It consists of a cast-iron front, and brick walls 12 to 16 inches thick, which inclose and carry the boiler. Where the flame strikes, or the temperature is high, there is a lining of one layer of fire-brick, laid with fire-clay. The side walls are prevented from bulging by vertical *buck-staves*, held together by through rods. Stays or other construction of wrought iron should not be exposed to the heat, as it tends to warp badly. It should be protected by brickwork; or cast iron, which is warped less by heat, may be substituted.

The water-tube types of boiler are supported on a frame made of iron beams, which is inclosed or filled in with walls of brickwork, as shown in Figs. 16 *a* and 16 *b*.

Grates. — The grate usually consists of fire-bars of cast iron, upon which the fuel rests. These bars are about $\frac{3}{4}$ to 1 inch thick; and the distance between them is from $\frac{1}{4}$ to $\frac{1}{2}$ inch, the rule being that for coal the open space between the grate-bars should be from $\frac{1}{4}$ to $\frac{1}{2}$ of the total grate area. For wood or for forced draught, the open space need not be more than $\frac{1}{8}$ to $\frac{1}{5}$ of the grate area. The depth of the grate-bars is about 2 inches at the ends, and 3 to 5 inches in the middle; and their length is from 2 to $3\frac{1}{2}$ feet. The grate has a maximum length of 6 or 7 feet, made up of two long or three short bars, end to end, and has a width of not more than 4 or 5 feet, in order to allow the fireman to properly feed it with coal. The grate-bars have projections at each end, and usually in the middle also, to keep them at the proper distance apart; and they are simply laid upon cross-bearers of iron, so as to be readily taken out. The thickness of the grate-bars should diminish towards the lower edge, in order to allow free entrance for the air and better escape for the ashes. Each square foot of grate surface will properly burn 15 to 18 lbs. of coal per hour with a good natural draught equal to, say, $\frac{3}{4}$ to

1½ inch of water. In the case of tubular boilers, the draught area through the tubes should not be less than one-sixth, nor more than one-quarter, of the grate surface.

By means of a forced draught, a much greater rate of consumption can be obtained; but this would not ordinarily be necessary or desirable in electric lighting. A steam-jet in the chimney, or some other means of forcing or aiding the draught, is often very convenient, however, in starting up the fire, or at times when the draught is poor.

Some form of rocking-grate, of which Fig. 19 shows an example, is usually desirable, particularly with anthracite coal. These

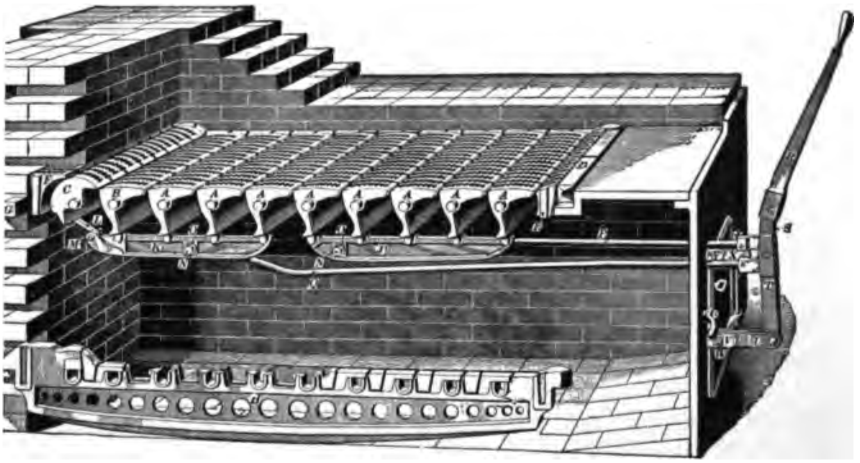


Fig. 19. McClave Rocking-Grate.

facilitate the work of the fireman. The removed portion, *H*, shown below, should rest at *G* and *D*, and carries the pins *A A*.

Boilers are sometimes "fired" by means of mechanical stokers, which are driven by a small steam-engine or electric motor, and act automatically to furnish the boiler with a continuous supply of coal. Uniformity of feed and saving of labor are secured by these devices, one form of which is shown in Fig. 20. The objection to mechanical stokers, in addition to their first cost and liability to get out of order, is the fact that they feed without regard to the demands upon the boiler, whereas a fireman can suit the supply of coal to the circumstances. Experience seems to show that the loss from this

cause with a mechanical stoker is about equal to the wages of the fireman; but the advantage of being rid of trouble from strikes and incompetent workmen might be a sufficient reason for their adoption. Favorable results with mechanical stoking are given in *London Electrical Review*, June 29, 1894, and *Electrical Engineer* (N.Y.), Oct. 11, 1893.

The construction of the chimney has been considered on page 68. The ordinary height of chimney required will vary between 75 and 200 feet. A well-proportioned chimney 175 feet high will give a draught of 1¼ inch of water, and with an internal diameter of 8 feet is sufficient for a 2,000 horse-power plant. The temperature of the gases in the chimney

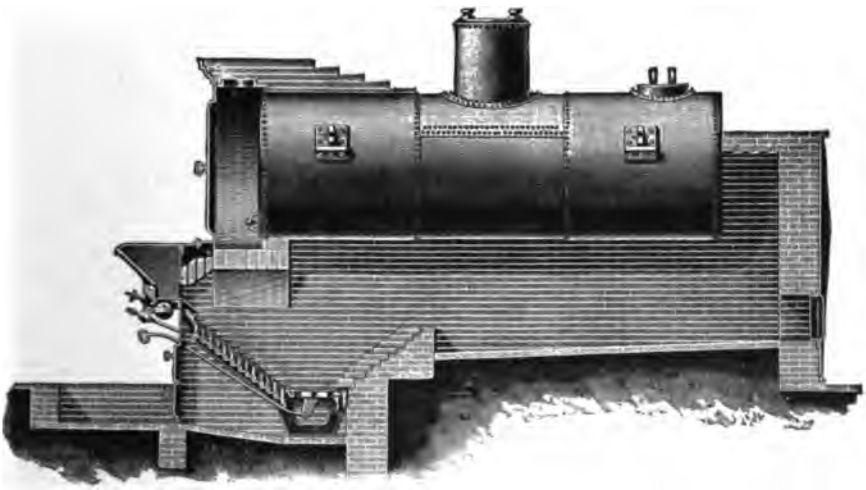


Fig. 20. Roney Mechanical Stoker.

should be from 200° to 250° C. Higher temperatures than this are not economical, since they do not greatly increase the draught, and they involve a large waste of heat. Where a number of boilers connect with the same flue leading to the chimney, care should be taken that they do not interfere with each other's draught. This may be avoided by putting a deflecting-plate in the flue at the point where each connects with the flue, this plate being bent in the direction that the gases should go. The main damper is put in the flue near where it enters the chimney.

Automatic damper regulators are quite commonly used in

electric-lighting stations, and usually give satisfaction. Of course they cannot be relied upon to keep a perfectly constant pressure; but their action is quite prompt and in the right direction, and tends to counteract great variations in boiler pressure. They usually operate by the direct action of the steam-pressure upon a piston or a diaphragm, the motion of which opens or closes the damper by means of a suitable mechanical connection.

Manholes. — A fire-tube boiler should be provided with one or more manholes, to allow a man to get inside to inspect, clean, or repair it. The hole is made oval in shape, partly to conform to the form of the body, and partly because a door of that shape can be passed through the hole, which is not the case with a circular door. A manhole is from 14 to 18 inches long, and from 10 to 13 inches wide.

Water-Level Indicators. — Two devices should always be provided on every boiler to show the exact height of the water in the boiler, these being the water-gauge and the test cocks or gauge. The water-gauge (Fig. 14) consists of two horizontal tubes leading into the boiler, one directly above the other, and connected by a thick glass tube. This should be placed at such a height that the normal level of the water is about halfway up the glass tube. Gauge-cocks consist of three small faucets, placed one above the other at such points that when the water is at its proper level the lowest one gives water, the top one gives steam, and the intermediate one gives mixed steam and water, when they are successively turned on to allow a little escape. These should be frequently tried, to make sure what the true water-level is; because the glass water-gauge is apt to become clogged, and give a false indication of the height of the water. The Manchester (England) Boiler Association attributes more accidents to inattention regarding water-gauges than to all other causes combined. Too low a water-level is one of the most dangerous conditions that can possibly exist in a boiler. Other means are also used to show the water-level, or to guard against its becoming too low. One of these consists of a float connected to a valve, which is opened when the water-level becomes too low, and the escape of steam causes a whistle to blow and give warning. Fusible plugs are also

placed in the boiler at such a height as to be covered by the water when it is at the proper level; but when it falls too low the plug is no longer kept cool by the water, and is fused by the heat of the fire, which allows the steam to escape, and warns the fireman.

Pressure-Gauge. — Every boiler must have an accurate and reliable pressure-gauge to indicate the exact steam-pressure. In addition to the ordinary gauge, some good form of recording pressure-gauge is recommended as giving a permanent record, and acting as a check on the fireman. The instrument may be placed in the office or engine-room, at any desired distance from the boiler, the full pressure being transmitted to it by a small pipe.

Safety-Valve. — This is simply a loaded valve which is lifted, and allows the steam to escape when the pressure rises above a certain amount. The load on the valve may consist of either a weight or a spring. The pressure-gauge and the safety-valve act as a check upon each other, and the failure of one would generally be indicated by the other; but since so very much depends upon them, they should be of the best possible construction, and should be carefully examined and tested at frequent intervals.

Feed-Water Purification. — The water used in steam-boilers is obtained either from the regular city water-supply, or from some source such as a pond, river, or well. Which of these is best to employ depends upon the circumstances in each particular case; but in almost every instance the question of the purity of the water is an important matter. Almost any water available for use in boilers contains from 10 to 100 grains of solid material per gallon; and since a 100 horse-power boiler evaporates about 30,000 lbs. of water per day of 10 hours, or about 400 tons per month, the accumulation of this material becomes very considerable, being from 75 to 750 lbs. per month, assuming only half of it to be deposited. Impurities in water are of two distinct kinds: First, small particles of solid material mechanically held in suspension, the presence of which is perfectly evident to the eye, forming what is called, in plain language, muddy or dirty water. The other class of impurities are mineral substances dissolved in water, producing little or no change in its appearance or transparency.

Impurities of the first kind can be removed by filtering, or by

simply allowing the suspended particles to settle; but impurities actually dissolved in the water can only be eliminated by some process of chemical or physical precipitation. The so-called "hard water" is simply water containing compounds of lime, magnesia, etc., in solution, which are particularly objectionable in water for boilers, since they are deposited as a scale or incrustation upon the interior, and seriously interfere with the transmission of heat through the metal, thereby reducing the efficiency of the boiler, and also introducing a danger that it will become excessively heated and weakened. These deposits in boilers sometimes reach a thickness of half an inch or more, and are extremely troublesome and difficult to prevent, or to remove after they have formed. It is estimated that scale $\frac{1}{16}$ inch thick necessitates the use of about 10 per cent more fuel, $\frac{1}{4}$ inch almost 40 per cent more, and $\frac{1}{2}$ to $\frac{3}{4}$ inch scale actually doubles the amount of fuel required to generate a given quantity of steam. These facts, and the greatly increased repairs and danger arising from scale in boilers, show the great importance of eliminating it.

Feed-water purifiers of various forms are employed to rid the

Fig. 21. Stillwell Feed-water Purifier and Heater.

water of these impurities. They usually consist of vessels or collections of tubes in which the water is heated, as represented in Fig. 21, the object being to deposit the impurities in the purifier, from which they can be easily removed, instead of in the boiler itself. Indeed, any form of feed-water heater (page 115) or economizer (page 115) also acts in the same way.

The chemical treatment of the water previous to introducing it into the boiler to remove the dissolved impurities is not particularly practicable, but in some cases it may be beneficial. For this purpose one may use some substance which, when added to the water, precipitates the foreign matter, so that it can be removed

by filtering, or by permitting it to settle. For example, carbonate of lime or magnesia is one of the most common impurities in water, but it is only soluble in water charged with carbonic acid; hence if milk of lime or caustic soda be put in the water, the carbonic acid combines with it, which causes the carbonate of lime to be precipitated. The sulphates of lime and magnesia, which next to the carbonates are the most common impurities in water, may be precipitated by adding carbonate of soda or soda-ash to the water. The precipitate, which is a white powder, may be removed from the water by filtration, or may be blown out of the boiler from time to time, and is far less objectionable than the hard adherent scale formed by the sulphates. Deposits in boilers may be removed by the simple operation of "blowing off," which consists in allowing a certain amount of water to escape from the mud-drum, thereby carrying away the dirt and precipitates which tend to collect in it. Actual cleaning with scrapers is necessary if the deposit has formed on the tubes or shell of the boiler, and has reached a thickness of $\frac{1}{8}$ or $\frac{1}{4}$ inch. There are many "boiler compounds" which are put into the boiler, and intended to dissolve, loosen, or otherwise get rid of the scale. These last remedies are somewhat similar to "quack medicines;" but they are quite popular in places where the hardness of the water gives great trouble, and is often so serious that almost any remedy is welcome. Oak, hemlock, and other barks, logwood and similar substances, are effective in water containing carbonate of lime or magnesia, by reason of their tannic acid, which produces a precipitate that is held in suspension, and does not deposit as scale; but the tannic acid is injurious to the iron, being apt to corrode it. The same objection applies to molasses, vinegar, fruits, etc., which have also been used; but their acetic acid eats away the iron.

Oil is frequently put into boilers to prevent the scale from adhering; but great care should be observed in its use, as it is likely to cause foaming and other troubles. The best oil is a high-grade kerosene; and any oil that is heavy (i.e. has "body") is very objectionable, because it tends to occasion foam, and also forms films or accumulations which prevent the water from coming in contact with the iron, thereby allowing the latter to become abnormally heated and producing weak or bulged spots.

Feed Pumps and Injectors. — The boiler is usually supplied

with water by means of a direct-acting steam-pump. This should preferably be double-acting, in order to maintain a steady flow of water; and the design should be as simple as possible, so as to reduce the danger of accidental interruption of the water-supply, which is a serious matter. The pump should be regulated to feed at exactly the right rate, so that it keeps a uniform stream of water flowing into the boiler through the heater; whereas, if the pump is stopped part of the time, the water in the heater will get too hot, and when the pump is started again at increased speed, to make up for the stoppage, it then tends to fill the boiler with cold water. The feed-pipe leading into the boiler should be arranged to give the feed-water a motion in the same direction as the natural circulation of the main body of water in the boiler, thereby aiding the flow.

There should be both a check-valve and a stop-cock between the boiler and pump. Without a check in the pipe the hot water is likely to back up on the pump, and make it difficult to start; and they are also needed in case of accident or repair.

The most necessary condition to the satisfactory working of the steam-pump is a full and steady supply of water. The pipe-connection should in no case be smaller than the openings in the pump. The suction-lift and delivery-pipes should be as straight and smooth on the inside as possible, and the total area of the strainer-holes should be from three to five times the area of the pipe.

When the lift of a pump is high, or the suction long, a foot-valve should be placed on the end of the suction-pipe, and the area of the foot-valve should exceed the area of the pipe. A foot-valve enables the pump to start off promptly and freely, as it avoids waiting for the suction-pipe to fill.

It is very essential that the suction-pipe should be absolutely air-tight, as a small leak will let in enough air to prevent the flow of water; and it should be as straight and free as possible.

The area of the steam and exhaust pipes should in all cases be fully as large as the nipples in the pump to which they are attached. The cylinders of steam-pumps should always be oiled before starting in the morning or stopping at night. In the ordinary boiler feed-pump the ratio between steam and water cylinders is about four to one in area, or two to one in diameter.

Stuffing-boxes on the piston and valve rods should in all cases be filled with soft, moist packing, because packing which is allowed to become hard and dry, will flute the rods, inducing leakage, and necessitating repairs. The air-vessels on the delivery-pipe of the steam-pump should never be less than five times the volume of the water-cylinder.

It is almost always advantageous, and at high speeds necessary, to connect a vacuum chamber to the suction-pipe near the pump, to avoid shock, particularly with long suction-pipes.

When pumps are stopped or are put out of service in cold weather, all the drain, drip, and pet cocks should be left open, and the steam-cylinder should be well oiled before stopping. The most economical speed at which to run the piston of a pump is about 100 feet per minute.

A steam-injector capable of feeding all the boilers should be provided in addition to the feed-pump, for use in case the latter fails. It is not desirable to use injectors all the time, however, since they are more wasteful of steam than a pump, especially if a condenser be employed in the plant, and the exhaust from the pump is run into it.

Feed-Water Heaters. — These should be provided in every electric-lighting installation, whether it be a large central station or a small isolated plant, in order to save as much as possible of the heat in the exhaust steam, and at the same time avoid feeding the boiler with cold water. The ordinary forms of feed-water heater consist either of a collection of pipes through which the feed-water is passed, and around which the exhaust steam from the engine circulates, thereby warming the feed-water, or the converse arrangement. The feed-water heater introduces no objectionable complication or trouble, being merely interposed in the pipe leading from the feed-pump to the boiler; and it seems to be generally desirable and advantageous for both condensing and non-condensing engines, even when the exhaust steam from the latter is used for steam heating. The Berryman heater is a well-known type, and consists of a series of inverted **U** tubes, through which the exhaust steam passes, and around which the feed-water circulates.

Economizers. — These, like feed-water heaters, have for their object the saving of escaping heat and the warming of the feed-

water; but in the economizer the heat is obtained from the waste gases on their way from the boiler to the chimney, instead of from the exhaust steam. The form and arrangement of the Green economizer, which is extensively used in this country and abroad, is shown in Fig. 22. The economizer of course tends to reduce the temperature of the gases in the chimney, and to that extent decreases the force of the draught. If, however, the gases leave the boiler at a higher temperature than is needed to give sufficient draught, then the reduction in temperature is not objectionable. If, on the other hand, the gases are cooled by passing through the boiler to as low a temperature as is compatible with a good

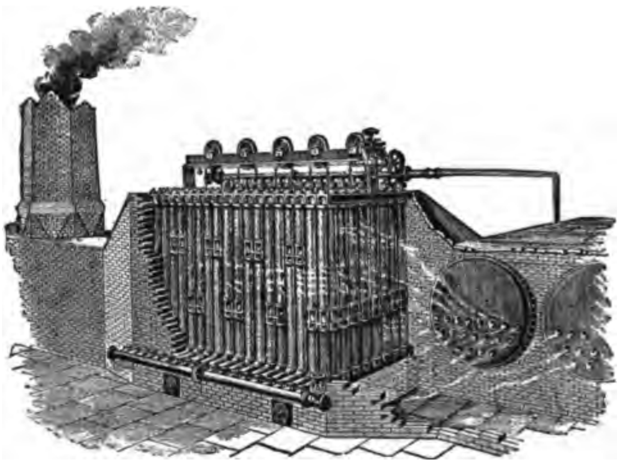


Fig. 22. Green Fuel Economizer.

draught, then the economizer evidently is undesirable, unless used in combination with mechanical draught. As a matter of fact, the economizer is practically an extension of the boiler; but the use of a separate economizer is a much better arrangement than combining it directly with the latter (by making a longer boiler, for example), since it enables the boiler as a whole to be run at a higher temperature and pressure, and avoids the introduction of cold water into the boiler proper. It would therefore seem that the economizer is particularly suited to cases where the steam-pressure is high, since the temperature of the boiler, and that of the waste gases leaving the boiler, would be correspondingly elevated. This and other forms of economizer

are very commonly adopted in electric-lighting plants, and are usually to be recommended, particularly when the steam-pressure is 100 lbs. per square inch, or more.

ARRANGEMENT OF BOILERS.

The vital importance in electric lighting of avoiding the least interruption in service, makes it necessary to take every precaution to insure absolute continuity in the working of the plant as a whole, even if an accident should occur to any one element. This is usually secured by having at least one, and if possible two or three, extra or reserve elements of each kind. In addition to having spare apparatus, it is also neces-

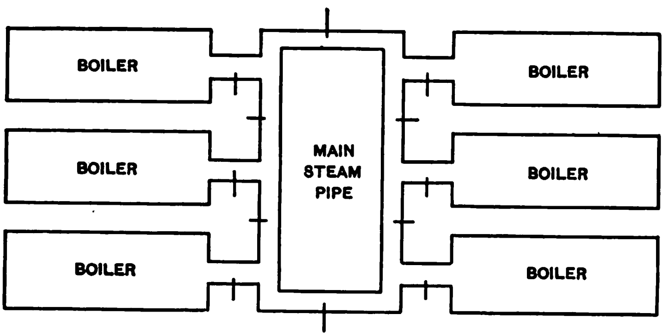


Fig. 23. "Ring" Arrangement of Boilers.

sary to adopt a carefully considered arrangement, in order that the breaking down of one element shall not prevent the use of the others. For example, if a number of boilers connect with one main steam-pipe, it might happen that an accident to that pipe at some point would cut off the supply of steam from all of the boilers. One way to provide against this trouble is to have what is called the "ring" arrangement of boilers, in which the boilers are placed in two rows, as represented in Fig. 23, and the main steam-pipe is a complete ring, so that accidents would have to occur simultaneously at two points in order to cut off any considerable number of boilers. There is a valve between each boiler and the ring-pipe, and also one in the latter between each boiler and the next, as indicated by short lines in the figure. This arrangement is an excellent one, and

is commonly adopted in central stations. The alternative plan of having in reserve an entire duplicate set of boilers or steam-piping and other apparatus, is an almost sure guaranty of continuity of service, but it involves considerable extra expense and complication, and does not appear to possess any great merit over the ring arrangement. But the special advantage of having a complete duplicate set of steam-piping in case of accidents or repairs might be worth the cost in an important plant, and many good engineers consider this to be the proper arrangement.

The separation of the boilers into groups, each having an independent steam-pipe, would tend to avoid the danger of a general breakdown; but it would sacrifice compactness, and increase the cost of, and the loss of heat by radiation from the piping.

A plan has been devised by Raworth,* consisting in arranging boilers in groups of three, the central one being used during the day when the load is light, and the unavoidable loss of heat from it keeps the boilers on each side warm and ready for use when the heavy load comes on in the evening. This is a good idea, but it is a question whether it would effect any considerable saving in actual practice.

Steam-Piping. — This matter is one of those details of construction which are very commonly neglected, and cause far more trouble than the principal elements of a plant. The pipe used should be of the best quality, made either of wrought iron or steel, and lap-welded. It should be of ample thickness to stand the pressure, but need not be extra heavy, as accidents usually happen at joints or valves, and not by actual bursting of the pipe. Flanges and fittings should be made of the best material, and very carefully put together. Leaky steam-fittings are very common, and cause much annoyance. The flange may be recessed or grooved to prevent blowing out of the gasket. The flange may be screwed upon the pipe, being careful to have exactly the same taper on both, which is a very essential condition to a tight joint. The joint is calked on the inside; and the small recess in the back of the flange around the body of the pipe is calked with Babbitt or steam metal, in case of leakage of the screw-joint when circumstances

* Fleming's *Alternate Current Transformer*, vol. ii., p. 343.

will not permit the joint to be opened and recalked inside. The screw-joint should be made with plumbago, to allow it to be unscrewed, if necessary, without breaking. The flange should be as strong at the bolt-holes as at other points, which is secured by having bosses around the latter. It is hardly possible to make the flanges too heavy, and for high pressures they should be made of steel, because the initial strain due to screwing them on the pipe is so great that hardly sufficient strength remains to withstand the steam-pressure and the expansive force due to the heat.

Steam-piping should be carefully arranged so that water will not collect in it, as it causes water-hammer effects, and if it gets into the engine cylinder it may wreck it. One plan is to have the pipe slope slightly downward all the way from the engine to the boiler; but the difficulty is that the steam tends to stop the back flow of the water, and carry it along with it. It is better, therefore, to have the piping slope toward the engine, and insert a steam trap or separator near the latter to eliminate the water. But in any case where a stream of condensed water runs along a pipe, it tends to cut a groove in the bottom of it. The latest and best practice consists in running a small pipe immediately beneath the main pipe, the two being connected at frequent intervals by short vertical pipes. The small pipe drains all the water out of the main pipe, and returns it to the boiler into which it leads.

Gaskets. — Corrugated gaskets of copper may be used in the case of mains where the ends of the pipe can be freely moved, or sometimes they may be omitted altogether in such a case, and the joint made iron to iron. But in the case of repairs, which are sure to come sooner or later, the line will be distorted more or less, and it will be almost impossible to bring the ends back to exactly the same position. For this reason it is better to use a thin gasket. This will allow for slight inequality in the faces and fitting of the flanges. Rubber gaskets will answer for low-pressure steam, but for high pressures of 100 lbs., or over, the temperature melts out the rubber, and copper gaskets should therefore be used.

Expansion Joints. — The ordinary slip-joint is not suited to high pressure, because it will not slide if the packing is adjusted

tightly enough to prevent leaking. Probably the best way to take up expansion in high-pressure systems is by means of long pipe-bends of considerable radius, or by joints which can turn slightly, both of which are shown in Fig. 24.

Valves. — These should be globe or gate valves, operated by an outside screw. The spindle should be of steel, and tinned, or of brass. The valve body should be extra heavy for high pressures, and in all cases stiffer than any other part of the system, to prevent any springing, which would cause the valve to leak. The seats of the valves should be bronze or brass. All valves with over 6 inches diameter of port should have a by-pass valve (i.e., a smaller valve about 1½ to 2½ inches in diameter) to equalize the pressure on both sides of the large valve before it is opened. This relieves excessive strain on the spindle and seats, and should always be used on high-pressure work.

Supports for Steam-piping. — A steam-pipe should rest when possible upon some solid support, and it is desirable to mount it upon rollers to allow for expansion. This will eliminate the vibration so often noticed, which racks and strains the whole system, and causes leaky joints. If supported from overhead beams, some good form of pipe-hanger is used, which should be carefully adjusted so as to preserve the alignment of the pipe, and at the same time allow for expansion.

Steam-Pipe Covering. — All pipes carrying live steam should be carefully covered with some material, to prevent loss of heat and condensation of the steam. Various materials are used for this purpose, such as mineral or slag wool, magnesia, asbestus, hair felt, and other similar substances. It is preferable that the material should be noncombustible. Several dealers make a specialty of supplying these coverings in various forms, to fit different sizes and shapes of steam-piping, elbows, valves, etc. These are usually held in place by thin metal straps; and when properly put on, and painted or whitewashed, they present a very neat appearance. The covering may also be applied in the form of plaster.

Good pipe-covering effects a very considerable saving by reducing condensation. The steam condensed in an uncovered steam-pipe 40 feet long and 4 inches in diameter is equal on the average to the steam consumed per horse-power by an ordinary

engine. The use of covering reduces the loss to one-quarter, or even to one-eighth as much, depending upon the thickness.

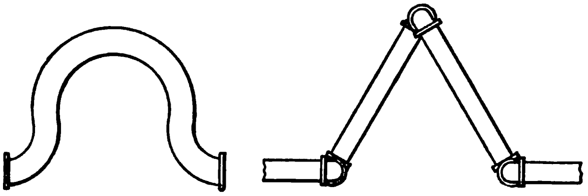


Fig. 24. Flexible Loops.

For more detailed facts regarding steam-piping see, "An Ideal Central Power Station," C. J. Field, *Electrical World*, Jan. 7, 1893; "Some Views of Central Station Work," T. Carpenter Smith, *Electricity* (N.Y.), June 1, 1892; "Steam Piping and Efficiency of Steam Plants," W. A. Pike, *Trans. Am. Soc. Mech. Eng.*, December, 1893.

Steam-Separators. — It is of the utmost importance that steam supplied to an engine should be as *dry* as possible. The significance of this is that steam or any other true vapor is made up of separate molecules, and is as transparent as air; but if small particles of water are present which have either been condensed or have not been evaporated, then it contains a larger amount of water than saturated vapor at that temperature and pressure. It then becomes cloudy, since the particles of water that are contained, though very small, are infinitely large compared to a molecule, and they intercept or reflect light. Tests of the percentage of moisture in steam, which usually varies from 1 to 10 per cent, can be made in various ways, a thorough method being described in the report of a committee on boiler-tests in Volume VI. of the *Transactions of the American Society of Mechanical Engineers;* but this is rather too elaborate and difficult for ordinary work. A simple method to approximately determine the dryness of steam consists in allowing a small jet to escape, and if it is transparent close to the orifice, or even a grayish-white color, the excess of moisture is probably less than 1 per cent. If the jet is strongly white close to the orifice, the excess of water is probably 2 per cent, or more. In making this test the steam should not be allowed to travel far in a naked pipe, because it tends to be condensed. Steam containing not more than 3 per cent of moisture is considered fairly "dry." The objections to wet steam are that

it introduces water into the cylinder, which might wreck the engine, it also increases cylinder condensation, and reduces the efficiency and output of the engine. It is therefore a requirement of a good steam-boiler that it should produce steam which is as dry as possible. This is secured by proper design, being largely dependent upon an ample surface for the disengagement of steam, and a sufficient steam space or reservoir in the boiler. If steam rises from a surface of water with a velocity greater than 2½ to 3 feet per second, it carries water with it in the form of spray. This velocity may be calculated by dividing the total volume in cubic feet per second of steam produced, by the total surface in square feet from which it rises. When the boiler throws a large amount of water into the steam it is called "priming," and may be due to impure water, which forms bubbles and foam, improper design of the boiler, or too high a water-level, which latter will reduce the steam-space, and bring the surface too near the outlet.

Fig. 25. The Stratton Separator.

The best way to obtain dry steam is, of course, to have the boiler generate it in the first place; but in case the boiler gives wet steam, either from improper design or impure water, or because it may happen to be working badly (which condition might occur in almost any boiler), then it is desirable to remove the water from the steam before it enters the engine cylinder. This is done by means of the various forms of steam-separator, one of which is represented in Fig. 25.

Management of Boilers. — Steam-boilers, being the most important and most dangerous element in an electric-lighting plant, should receive the greatest possible care, and particular attention should be given to the following points, to insure *safety*: —

Safety-Valves. — These should be of ample size, and in perfect working-order. Neglect or overloading might lead to the most disastrous results. They should be tried at least once every day, to see that they act freely.

Pressure-Gauge. — This must be absolutely accurate; and if there is the slightest doubt about it, it should be compared with a standard gauge. It should stand at zero when the pressure is off, and should show the same pressure as that for which the safety-valve is set, when the latter is blowing off.

Water-Level. — The engineer should make absolutely sure that the water is at the proper height in starting up, or at the beginning of each watch. The glass gauges should not be relied upon entirely; but the gauge-cocks should be tried, because the passages in glass gauges are apt to become clogged and give a false indication of the height of the water, which might be much lower or higher than that in the glass tube.

Low Water. — In case the water-level falls too low in the boiler, immediately cover the fire with ashes (wet if possible) or earth. If nothing else is handy, use fresh coal, taking great care, however, to put on a sufficient amount to deaden, and not to increase, the fire. Draw the fire as soon as it can be done without increasing the heat. Do not turn on the feed-water, start or stop the engine, or lift the safety-valve, until the fires are out and the boiler cooled down.

Blisters and Cracks. — Either are likely to develop even in the best plate-iron; but at the first indication they should be carefully examined, and the boiler put out of service and repaired.

Fusible Plugs. — If used, these should be examined when the boiler is cleaned, and carefully scraped clean on both the water and fire sides.

The attention required to secure *economy* is as follows: —

Firing. — The coal should be thrown on evenly and regularly, a little at a time. Moderately thick fires are most economical, but thin fires must be used when the draught is poor. The grate should be kept evenly covered, and no air-holes in the fire allowed to form.

Cleaning. — All heating-surfaces must be kept clean inside and out, to avoid serious waste of fuel. The frequency of cleaning depends upon the nature of fuel and water. As a rule, not over $\frac{1}{16}$ or $\frac{1}{8}$ inch of scale or soot should be permitted to collect on the surfaces before cleaning.

Foaming and Priming. — This can usually be checked by reducing the outflow of steam, or by decreasing the draught of the

fires. Slightly opening the blow-off and increasing the feed will remove impure water. The water-level may be lowered if high enough to permit of it.

Blowing off. — If feed-water is muddy or salt, blow off a portion frequently, according to condition of the water. The boiler should be emptied every week or two, and filled up entirely fresh; but the boiler should not be emptied while the brickwork is hot.

Durability. — Deterioration or injury to boilers is avoided by general care; certain special points may be noted: Cold water should not be put into a hot boiler; dampness should not be allowed on the outside of the boiler, as it tends to corrode and weaken it; the boiler should not be fired up too rapidly or too intensely. If a boiler is not required for some time, it should be emptied and dried thoroughly. If this cannot be done, it should be filled with water, into which is put a quantity of common washing-soda.

Testing Steam-Boilers. — Tests of steam-boilers * are made to determine the quantity and quality of steam that they supply, the weight of fuel required to produce a certain amount of steam, and other similar facts. A boiler-test requires considerable knowledge, care, and skill, as well as accurate apparatus.

The principal points to be ascertained and noted in a boiler-test are: —

1. The type and dimensions of the boiler, including the area of heating-surface, steam and water space, area of water surface, and draft area through or between tubes or flues.

2. The kind and size of furnace; area of grate, with proportion of air-spaces in it, height and size of chimney, length and area of flues.

3. Kind and quality of fuel, and amount of ash and water therein. The latter is a more important item than is generally understood, as it not only adds to the weight without increasing the value of the fuel, but the heat taken to evaporate and send the steam up the chimney in a highly superheated condition adds to the unobserved waste.

4. Temperatures of external air, of fire-room, of chimney gases, of fuel, of water, and of steam.

5. Pressures of the steam, of barometer, and of draught in chimney.

6. Weights of feed-water, of fuel, and of ashes. Water-meters are not reliable as an accurate measure of feed-water.

7. Time of starting and of stopping test, taking care that the observed conditions are the same at each as far as possible.

* This subject will be found very fully treated in the report of a committee to the American Society of Mechanical Engineers, and the discussions on the same. *Transactions A. S. M. E.*, vol. vi., pp. 256–351.

8. The quality of the steam, whether "wet," "dry," or "superheated."

From these data all the results can be calculated, giving the economy and capacity of the boiler, and the sufficiency or insufficiency of the conditions, for obtaining the best results.

The amount of water evaporated per pound of coal is universally conceded to be the proper measure of the efficiency of a boiler; but in order to compare one boiler with another, each should have equally good coal, be fed with water at the same temperature, and furnish steam at the same pressure. As this is impracticable in testing, a standard has been accepted to which all tests should be brought for comparison. This is called the "equivalent evaporation from and at 212°" per pound of combustible; that is, what the evaporation would have been if the coal had been without ash, the feed-water at boiling-point, and the steam delivered at atmospheric pressure.

It may be determined by the following formulæ: —

Let W = the observed evaporation per lb. of combustible.
t = the observed temperature of feed.
T = the temperature of steam at observed pressure.
H = the total heat of steam at the observed pressure.
W' = equivalent evaporation from and at 212°.

$$W' = W\left(1 + \frac{0.3\,(T - 212) + (212 - t)}{966}\right);$$

$$\text{or, . . . } W' = W \times \frac{H + 32 - t}{966}.$$

The value of T and H may be found by reference to "steam-table" on page 92.*

Steam-Boiler Economy. — Correct design, construction, and management of the boiler-plant is a most important item in an electric-light station. Forcing the boilers beyond their capacity, wastefulness in the use of coal, or other such loss, might result in the financial ruin of the entire enterprise. On the other hand, raising the evaporation from 7 to 8 lbs. of water per lb. of coal, represents a saving of about 14 per cent, which would fully warrant an expenditure for improvements to secure this saving equal to one whole year's coal-bill, since it would pay 14 per cent on the investment.

Claims are often made as high as 11 or 12 lbs. of water evaporated per lb. of coal; but in regular practice it is difficult to do better than 10 lbs., and even 9 lbs. is a very good ordinary result.

Boilers are rated on the basis of 30 lbs. of water evaporated per horse-power hour, at 70 lbs. pressure, feed-water being 100° F.; but as there are engines which require only 20 lbs., or even as little as 15 lbs. of water, this rating is somewhat nominal.

* The two preceding pages are compiled from *Steam*, Babcock and Wilcox, 1894.

CHAPTER X.

STEAM-ENGINES FOR ELECTRIC LIGHTING. GENERAL CONSTRUCTION.

Classification. — Engines may be divided into various classes for convenience of reference, according to their form, action, or purpose. For example, engines are either *horizontal*, *vertical*, or, in rare instances, *inclined*, according to the position of the cylinder or cylinders.

An important distinction, particularly in engines used for electric lighting, exists between *low-speed* and *high-speed* engines. It is impossible to draw a definite line between the two classes; but in a general way it may be said that low-speed engines usually run at less than 150 revolutions per minute, the ordinary speed being from 50 to 100, whereas the customary rate of high-speed engines is from 200 to 350 turns per minute.

Engines may also be divided into classes, depending upon the important matter of speed governors. There are *throttle-valve* and automatic *cut-off* engines. In the former, the speed is controlled by partially shutting off and reducing the pressure of the steam allowed to enter the cylinder. In the latter, the steam enters the cylinder at approximately the full boiler pressure; but the governor causes the supply to be entirely cut off at a certain fraction of the stroke, depending upon the speed of the engine.

Engines are divided into *simple* and *compound*, according to whether the steam expands completely in one cylinder, or partially expands in one cylinder, and then passes to another cylinder or cylinders, in which it is further expanded. Engines are called *compound*, *triple*, or *quadruple expansion*, according to whether the steam is expanded twice, three times, or four times, respectively.

GENERAL CONSTRUCTION OF STEAM-ENGINES.

The general construction of steam-engines will be considered in the present chapter, and then the special discussion of the various typical forms will be taken up in the next chapter.

The principal parts of a steam-engine are the cylinder, piston, piston-rod, valve, governor, mechanism connecting the piston-rod and fly-wheel, fly-wheel, bearings, and the base or frame supporting all these various parts.

The Cylinder. — This is usually a simple cylinder of cast iron, accurately bored inside, and ending in faced flanges, to which the ends or covers are bolted. Since the cylinder has to withstand the internal pressure of the steam, it should be of sufficient thickness; but usually its strength far exceeds that required to sustain the steam-pressure, for the reason that, being made of cast iron, it can be quite thick without involving any considerable expense; and it is also desirable to have it of ample thickness, in order to allow it to be re-bored when worn, and to prevent it from bending or warping to the least extent by the very heavy mechanical strains to which it is subjected. One end of the cylinder is provided with a stuffing-box, which allows the piston-rod to slide freely back and forth, but prevents the steam from leaking out. At the two extreme ends of the cylinder are the ports, through which the steam alternately enters and leaves the cylinder. These ports are connected by suitable passages to the steam-chest, in which works the valve which controls the inlet and outlet of the steam.

The principal points to be observed in designing steam-cylinders are, the proper proportions and thickness of the various parts to give ample strength, and the perfect boring and fitting of the same. The proper length and diameter of the cylinder depend upon circumstances, and considerable difference of opinion in regard to this question exists among authorities and builders. Ordinarily the stroke of an engine is from $1\frac{1}{2}$ to $2\frac{1}{2}$ times the diameter of the piston. The length of the cylinder must, of course, be equal to the stroke plus the thickness of the piston and the clearances at both ends. Usually the total length of the interior of the cylinder is about twice the diameter.

Sometimes cylinders are "jacketed;" that is, surrounded with a space which is filled with steam in order to warm the cylinder itself. Steam-jackets are rarely used, however, except in cases where the steam-pressure, and therefore temperature, is very high, or the ranges of temperature very great. Its complication and cost of construction are the principal objections to it.

Some covering of nonconducting material, such as wood or felt, called lagging, should be applied to steam-cylinders, in order to reduce the loss of heat, and cylinder condensation.

The Piston is the part which is driven back and forth in the cylinder by the pressure of the steam; and from it the entire power of the steam is obtained, its area multiplied by the steam-pressure per unit of area being the total pressure exerted upon it. If the piston were driven by a constant steam-pressure, it would be desirable to make it as light as possible, to avoid wear and the effect of its inertia at the ends of the stroke. But in all economical engines the pressure varies greatly, because the steam is cut off and acts expansively during the greater part of the stroke; hence it is customary to design the piston to have sufficient weight so that its inertia takes up the excessive pressure of the steam in the beginning, and gives up energy toward the end of the stroke, when the pressure is low, thus aiding the compression of the steam on the other side of the piston. The piston is made steam-tight in the cylinder in various ways, the usual plan being to surround it with split rings of cast iron, steel, or gun metal, which are made to have a tendency to spring outward slightly, and thus fit closely against the walls of the cylinder. Two or more of these rings are placed side by side, and arranged so that the joints are not in the same line. These rings are held in place by recesses or grooves turned in the periphery of the piston. The relative diameter and thickness of pistons depend on the particular type of engine, the advantage of a long piston being that it tends to diminish leakage and wear, and it can be made hollow, so that it is not very heavy; but it necessitates an increase in the total length of the cylinder. *The piston-rod* is usually made of steel, and is connected rigidly to the piston by a shoulder formed upon it, and a nut at its end.

The Stuffing-Box prevents the leakage of steam around the piston-rod. It consists simply of a cylindrical projection cast on the cylinder cover, its internal diameter being somewhat larger than the piston-rod which it contains. The space between is filled with some form of packing, which is held in place and adjusted by a loose piece termed the *gland*. The gland is attached to a flange at the outer end of the stuffing-box by suitable bolts and nuts. An almost infinite number of devices and materials

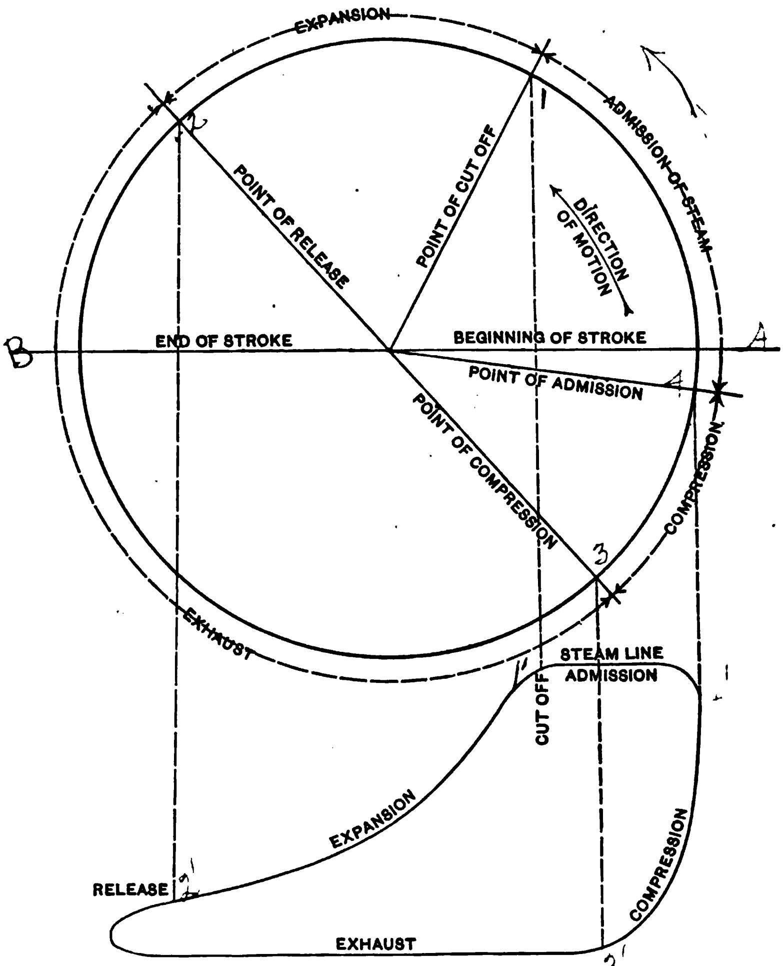
have been employed as packing in stuffing-boxes. The ordinary kinds used are hemp, asbestus, or some other fibrous material mixed with tallow, india rubber, etc., to make it steam-tight. Graphite, fine particles or shavings of metal, and similar substances, have also been employed in packing. These soft packings are usually applied either in the form of rings or rope, the latter being wound spirally around the piston-rod. Rings of Babbitt or other metal are also used. The packing of the piston often causes annoyance, since it is very likely to be either too tight or too loose, and wears so rapidly that it requires constant adjustment.

Valves. — The most delicate parts of a steam-engine are the valves, and the mechanism which operates them. The function of the valves is to control the entrance and exit of the steam to and from the cylinder, so that it shall occur at exactly the right moment, and continue for exactly the proper period of time. Three kinds of valves are very commonly used in steam-engines, these being *slide valves*, *piston valves*, and *rotary valves*. The advantage of the slide valve is that it is easily fitted. In fact, it naturally tends to wear itself into a more perfect fit, and a certain amount of wear can occur without causing leakage or requiring refitting. It has the disadvantage, however, that it is not so easily balanced; that is to say, the steam tends to force it against its seat with excessive pressure. The advantages of the piston valve are that it is easily balanced, so that the pressure caused by the steam is equal in all directions; and for a given sized valve a large opening of port is obtained with a small motion, since the port can extend practically all the way around the valve. The objection to a piston valve is the fact that if it wears even very slightly, it becomes smaller than the cylinder in which it works, and is apt to leak. To refit it requires either a new piston, or the valve-seat must be bored out and a bushing inserted which fits the piston. Special devices have been invented to take up the wear of a piston valve. (See Mackintosh and Seymour engine in the next chapter.) The rotary valve has advantages similar to those of the piston valve; in fact, an even smaller motion will cause a large opening of the port, but it also has the defect that it is difficult to adjust for wear. Rotary valves have, however, long been used very successfully in the Corliss types of engine.

Valve Gear. — The valves are caused to open and close in

almost all types of engines by one or more eccentrics placed upon the main shaft of the engine. The eccentric is practically a form of crank with the crank-pin enlarged sufficiently to include the main shaft within its section. It ordinarily consists of a sheave

MOTION OF VALVE

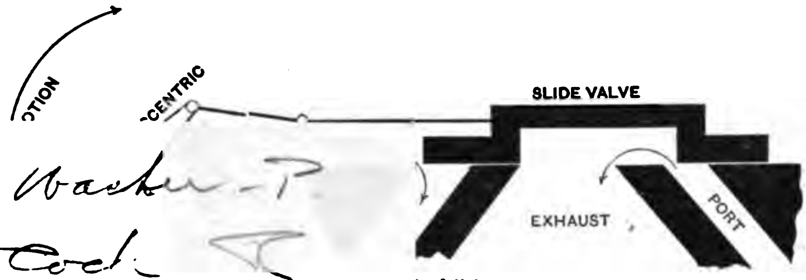


INDICATOR DIAGRAM.

Fig. 26. Action of Valve and Steam.

or disk of cast iron surrounded by a strap or ring which connects it with the eccentric rod, the latter being connected directly or indirectly to the valves. When the main shaft revolves, the

eccentric automatically opens and closes the valve. It is possible by one simple eccentric and slide-valve to obtain quite a perfect action of steam in the cylinder. This is done by proportioning



Lead Washer – P

Stat. Cock

[illegible] F

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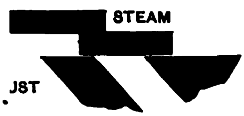
' of Valve.

ɔw of the eccentric, and the rela-
of the valve, in such a way that
ɔre the commencement of each



p of Valve.

ɔressure in the cylinder. The
: *lead*, is secured by setting the
advance of the crank, as repre-
the valve are also made wider
the valve is in its middle posi-
ɔort, as represented in Fig. 28.
ɜfore the end of the stroke, and
:essary to obtain economy. The
m or induction edge A, of the
that on the exhaust or eduction
p. The former is usually made
:d in Fig. 28, in order that the
widely to exhaust than to take
steam, which diminishes the back pressure. In other words, it is obviously objectionable to limit the outlet of the steam in the same manner as the inlet. The outside lap necessitates a still further angular advance of the eccentric, with respect to the crank, in order to open the valve at the beginning of the stroke,

as shown in Fig. 27. It is customary, particularly in high-speed engines, to close the exhaust a little before the end of the stroke, and obtain what is called compression, or cushioning, which tends to relieve the shock due to reversing the motion of the piston and other parts. This also raises the steam remaining in the cylinder to a pressure similar to that of the boiler, thus avoiding the impact which would occur if high-pressure steam were suddenly admitted to a space having a pressure only equal to that of the atmosphere. In Fig. 26, the position and action of the valve is represented in the circle above, and the action of the steam in the cylinder is shown in the indicator diagram below. A study and comparison of these will give a clear idea of the principles of valve-action and steam-distribution in engines. The ordinary slide-valve, considering its simplicity, gives a remarkably good action of the steam in the cylinder; but to obtain a really perfect effect, and to cause the admission, cutting off, and the release of the steam, as well as the closing of the exhaust, each to occur at the proper instant, and to enable them to be independently adjusted, it is desirable to separate the valve functions of admission and exhaust of steam. This can be done by the use of two valves driven by separate eccentrics, one acting in the ordinary way to control the general distribution of the steam, and the other operating to cut off the steam at the proper point, or by the use of three or four separate valves, each performing one or more of the functions of the single valve described above.

The special forms of valve-gear for obtaining economy, regulation, and other effects in the working of steam-engines, are best described in connection with the various types of engines which have been developed as a result of years of experience, and in which the valve mechanism is the most important and distinctive feature. These are given in the next chapter.

The Governor. — An engine which always works with a constant load would have a constant speed, provided the steam-pressure did not vary. In practice, however, the load on a steam-engine changes from time to time; and in electric lighting, although these changes are rarely sudden, nevertheless they are very great, since the number of lights in the daytime may be very small, and in the early evening the engine may have to carry its full rated load. The fly-wheel, which will be discussed later, acts

to prevent sudden or transient changes in speed due to variations in the load on, or power of, the engine during a single stroke; but something is required to regulate for changes in load that are permanent, or at least last for several strokes.

The device used to secure this control of speed is called a governor; and it acts either to regulate the supply of steam by changing the opening, to a greater or less extent, of a valve in the main steam-pipe, or by automatically changing the point in the stroke at which the steam is cut off. These two types are called, respectively, *throttle-valve* and *automatic cut-off governors;* and either of them requires to be adjusted to admit just sufficient steam to give the power necessary to maintain practically the same speed, whatever the load may be. The throttle-valve governor was the only one employed up to the time when Corliss invented and introduced his remarkable automatic cut-off valve-gear, that is one of the greatest improvements in steam-engines since the time of Watt, and which to this day is used, with only slight modifications, in many of the largest and best stationary engines in America and Europe.

The throttle-valve governor is not usually considered advisable in this country, except in small or unimportant engines. It has the defect that it acts to destroy a portion of the pressure of the steam, or "wire-draw" it. This obviously reduces the efficiency of the engine; but the superheating of the steam which results from its being "wire-drawn" through the throttle-valve almost makes up for the loss of pressure by diminishing cylinder condensation. The Willans engine (see next chapter), which is extensively used in English lighting-plants, and is now being introduced into this country, has a simple throttle-valve governor. It is claimed that this engine gives economical results in actual use that are fully equal to, if not better than, those obtained by automatic cut-off engines, probably because the loss, due to diminished pressure, is partly offset by the gain due to superheating, as already stated. Furthermore, stations employing Willans engines usually subdivide the power into a number of units, only a sufficient number of engines being run to properly carry the load, thus making it unnecessary to throttle the steam-supply, since the engines are almost always running at or near full load, and the governors only require to regulate for small

fluctuations. Willans engines are compound or triple expansion, which also tends to make them economical. An automatic cut-off governor, on the other hand, allows the steam to enter the cylinder at full pressure for a certain fraction of a stroke, and then the steam is suddenly cut off. This is theoretically and practically a more economical use of steam, and would seem to be very important in engines working at light load for any considerable portion of the time. But, unfortunately, cylinder condensation (described later in the present chapter) causes great losses, particularly with an early cut-off, which the superheating due to throttling reduces, as we have seen; consequently, the automatic cut-off is not so much better than the throttle governor as it has generally been supposed to be.

The throttle-valve governor is very simple in its construction, being merely a pair of weights suspended from a vertical spindle, and caused to revolve by connecting it with the main shaft through gearing or belting. When the speed rises above the proper point, the weights fly out by centrifugal force, which partially shuts the valve in the steam-pipe by means of levers and rods.

The automatic cut-off governor exists in many different forms, which, however, may be arranged in two general classes. First, those in which the cut-off is controlled by a centrifugal governor similar to the device just described, Corliss engines being of this type. Second, those forms of governor which are mounted upon, and revolve with, the main shaft of the engine, and are called *shaft-governors*. This latter type has several very important advantages; being carried by the main shaft, it does not have to be driven by belting or gearing, which involves complication, indirectness, is more or less unsightly, and likely to fail and allow the engine to race. The shaft-governor, being upon the shaft, is directly connected to the eccentric, and thereby controls the action of the valve effectively and conveniently; but a shaft-governor requires a considerable speed of rotation in order to give sufficient centrifugal force to operate it, and is therefore only applicable to high-speed engines of 200 or more revolutions per minute. The shaft-governor contributes more than any other element to the compactness, perfection of regulation, and general success of the high-speed automatic cut-off engines

which have been so very extensively used for electric lighting in America, and are so convenient for small plants.

Any form of governor in order to give perfect regulation, that is, maintain a constant speed, must be designed in accordance with certain mechanical principles. The general condition to be fulfilled is that the governor must move from one limit of its throw to the other with a very small change in speed, usually about 1 or 2 per cent. *This requires that the centrifugal force shall be practically equal to the force due to the spring or weight which opposes the centrifugal force, in every position of the governor-weights.* A governor of this sort is called *isochronous*, since it will only run at one speed; and the slightest excess of speed will cause the weights to fly out to their extreme limit, and either throttle or cut off the steam, so as to bring the speed

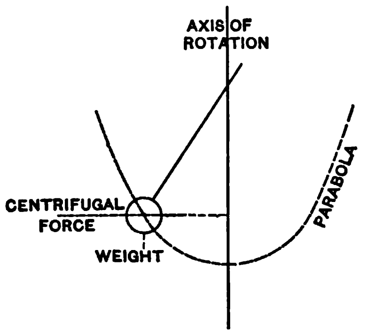


Fig. 29. Theoretical Parabolic Governor.

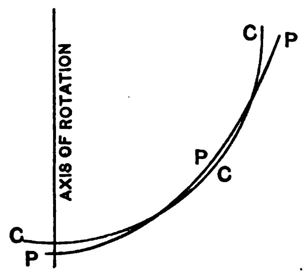


Fig. 30. Practical Governor.

down again to its normal value. Theoretically, if the weights move in the arc of a parabola, as represented in Fig. 29, the effect of the centrifugal force and gravitation is exactly balanced at every point for a certain speed. In practice it would be difficult to arrange the weights to move in a path of this form; and they are therefore suspended by an arm from a pivot, and move in the arc of a circle, *CCC*, which is made to approximate as closely as possible to the ideal parabola, *PPP*, as indicated in Fig. 30. As a matter of fact, the difference is less than that shown in the figure, and the arc of motion is also less; indeed, it is probably better than if the ideal curve could be attained, since a governor which is perfectly isochronous would be too sensitive, tending to shift back and forth from one end of its path to the other.

"Hunting" of Engine-Governors. — The motion of governors which is called "hunting" is usually caused by the fact that the forces are adjusted for nearly perfect synchronism, so that when the speed increases, the friction and inertia of the parts prevent them from acting instantly; but when the governor does act, it flies to the limit of its range, and thereby reduces the supply of steam and the speed too much. The converse of this action then takes place, and so on, thus causing objectionable fluctuation in speed. The usual way to prevent this hunting or overshooting of an engine-governor is to provide it with a dashpot, consisting of a cylinder containing a piston, and having only a very small hole for letting air in or out, thus making the motion of the governor gradual and steady, without interfering much with its sensitiveness. Anything which makes a governor "stick," and fail to start promptly, will tend to cause "hunting," and should be carefully avoided by lubrication and adjustment of the parts. If the governor is too small, the force which it exerts is not sufficient to affect the valve until the speed has changed considerably, which would also cause hunting. This is avoided by making both the centrifugal force of the governor-weights, and the force which balances it, great, so that a small *percentage* of difference between them will have considerable actual value.

For example, if the centrifugal force of the weights at the proper speed is 1,000 lbs., and it is exactly balanced by the force of a large spring, then a variation of 1 per cent in speed will cause a change of about 2 per cent in centrifugal force, which gives an effective force of 20 lbs. to cause the action of the governor. The tendency to hunting is usually greater at very light loads than at half load or more, the effect of the load being to steady the governor.

Another method of securing considerable force to control the valves is to adopt some relay arrangement; that is, the governor proper merely puts a screw or hydraulic mechanism into action. In this way the governor itself may be made small and with little friction; at the same time the force which actually regulates the valve may be considerable. This indirectness tends, however, to introduce a certain time-lag in the action, which also causes the governor to hunt.

If a spring be employed to give the centripetal force which holds the governor-weights from flying out, isochronism may be obtained by adjusting the length, tension, and angle of the spring so as to approximately balance the centrifugal force in all positions. This can be applied either to the ordinary vertical form of governor, or to a shaft-governor, the latter being always made in this way.

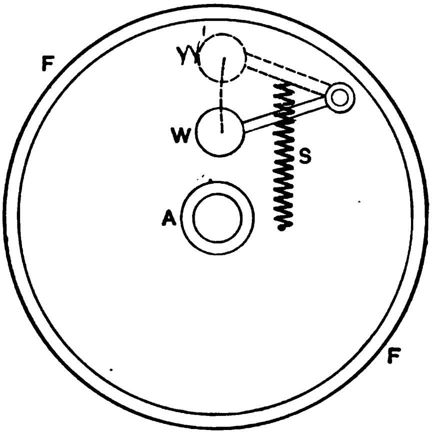


Fig. 31. Principle of Shaft Governor.

The general principle of these latter governors is shown in Fig. 31, in which *FF* is the fly-wheel, rotating on the shaft *A*. The governor-weight *W* is pivoted so that it swings out in practically a radial line from the center of the fly-wheel. The spring *S* is adjusted so that at the innermost position of the weight the spring tension is exactly equal to the centrifugal force at the correct speed. The length of the spring must then be such that its tension increases directly as the distance of the weight from the center increases; that is, when the weight flies out to a position indicated by the dotted lines, and is twice as far from the center, the tension of the spring will then be doubled: and since centrifugal force increases directly with the radius at a constant speed, it follows that the centrifugal force and spring tension will always be balanced at that particular speed. But if the latter falls even slightly, the centrifugal force is less than that of the spring in every position, and the weights move all the way inward, causing the valve to admit more steam, thus keeping up the speed, or *vice versa*. "Hunting" is prevented by dashpots or other means described above.

Dynamometric Governors in which the steam-supply is regulated in proportion to the load transmitted have also been used. These are theoretically more perfect than a centrifugal governor, since the latter requires a change of speed in order to act, and therefore permits the very thing it is intended to prevent;

nevertheless, dynamometric governors have not been successful, probably for the reason that they have the inherent fault of being in unstable equilibrium. Assume, for example, that the speed accidentally increases slightly above the normal, as it is certain to do occasionally, then this excess of speed tends to make the resistance to rotation greater; that is to say, it would have an effect similar to a slight addition of load. This would cause the dynamometer to increase the supply of steam, which would still further augment the speed, and thus the trouble would become aggravated. It would require a speed-governor as a check on the dynamometer, hence the latter is superfluous.

Electromagnetic Governing Devices have been applied to steam-engines with some success; and they would seem to be the best means to regulate engines used for driving dynamos, since they would enable the speed and power of the engine to be directly controlled by the current generated, which the steam-engine governor has for its real and ultimate object. Such a governor is quite simple in principle, and consists of an electromagnet or solenoid fed with current from the dynamo, which is driven by the engine. When the current becomes excessive, the electromagnet attracts its armature against the force of a spring or gravity, and the motion of the armature operates the valve by suitable mechanism, reducing the supply of steam, and thus bringing the speed and current back to the proper point. The coils of the magnet can either have a great many turns of fine wire connected in parallel with the main circuit, to maintain a constant potential, or they may consist of a few turns of large wire connected directly in series with the main circuit for constant-current working. The device is adjusted by varying the pull of the weight or spring.

For a full treatment of the theory and construction of steam-engine governors, the reader is referred to Thurston's *Manual of the Steam Engine*, Part II., pages 360 to 413. The hunting of governed engines is discussed by James Swinburne in a paper with this title read before the British Association, Oxford, 1894.

Connecting-rods are used in engines to connect the piston-rod with the rotating-crank, and act to convert the reciprocating motion of the piston into the rotary motion of the shaft. They

should be made of steel, since they are subjected to considerable strain, due to the push and pull of the piston, and in high-speed engines the up and down throw of the connecting-rod tends to bend it transversely, first one way and then the other, and sometimes breaks it, causing a serious accident. For this reason the connecting-rods of high-speed engines are made of rectangular cross-section, the dimension in the plane of its motion being two or three times the other dimension. The length of the connecting-rod is very rarely less than twice or more than three times the length of stroke. Greater length decreases the obliquity and the side-thrust on the cross-head referred to below, but it makes the rod heavier as well as weaker. The adjustment of the tightness of the connecting-rod end on the crank-pin is one of the troublesome points in handling an engine. If it is too tight, the crank-pin will heat; and if too loose, it will "knock," due to lost motion. A very slight looseness, with barely perceptible knocking, is safest; since a hot crank-pin is far more objectionable than a little noise, and it is impossible to make the proper adjustment while the engine is running.

Cross-heads and Slides. — The cross-head is the name given to the part which connects together the piston-rod and connecting-rod of a steam-engine, and moves back and forth in the slides, thus guiding the outer end of the piston-rod.

In good practice the rubbing surface of the cross-head is such that if V be the velocity (piston speed) in feet per minute, and p be the pressure in pounds per square inch, then * —

$$pV < 60{,}000, \quad \text{and} \quad pV > 40{,}000.$$

Piston speeds are usually between 300 and 800 feet per minute, and the allowable pressure is about 60 pounds per square inch for high-speed to 150 for low-speed engines. This p includes the sum of all the pressures forcing the two rubbing surfaces together, but is almost entirely due to the thrust caused by angular position of the connecting-rod with respect to the piston-rod, being zero when the two are in a straight line, and a maximum when the connecting-rod and the crank are at right angles. If the engine turns "over," that is, the crank moves forward in the upper half of its revolution, then the

* Thurston's *Manual of the Steam Engine*, Part II., p. 92.

pressure of the cross-head on the slides is always downward, and the surfaces are easily kept lubricated. But if the crank turns in the opposite direction, — that is, the engine turns "under," — then this pressure is always exerted upward, which renders lubrication much more difficult, since the oil tends to run off of the rubbing surfaces. Nevertheless, on account of the belting,* and for other reasons, engines are sometimes run in a left-handed direction; but it should be avoided if possible.

The Fly-wheel has for its object the maintenance of a steady speed in spite of the variations in action which occur. These variations are of three general kinds: change in the steam-pressure due to expansion, variation in the leverage at which the piston acts on the rotating-crank, and variations in the load on the engine.

In electric lighting, the two former causes of variation must be carefully guarded against, since even slight fluctuations in speed at different parts of the stroke would produce very disagreeable flickering in incandescent lamps. This is often perceptible; and it is possible to count the strokes of the engine by observing the lamps themselves, or a white surface placed near them, the latter being a more sensitive test. The changes in load which occur in electric lighting are gradual if lamps are turned on and off a few at a time, as is ordinarily the case; and the governor of the engine acts to maintain a nearly constant speed. But if a number of lamps are suddenly lighted, in a theater for example, or if a short circuit occurs, the fly-wheel should keep up the speed until the governor has time to act. In practice, however, calculations of the size of the wheel required cover only the first two causes of variation enumerated above; since the sudden changes in load are of indefinite value, particularly in the case of a short circuit, and the fly-wheel is only expected to take care of ordinary fluctuations of this kind.

The weight of fly-wheel required may be determined as follows: —

N = effective horse-power of the engine.
n = number of revolutions per minute.
G = weight of fly-wheel rim in lbs.

* See Chapter XV.

v = mean speed of rim in feet per second.

$$\frac{1}{d} = \frac{v\text{ max.} - v\text{ min.}}{v} = \text{coefficient of fluctuation of speed.}$$

For a single cylinder engine we have, $G = C\dfrac{dN}{v^2 n}$.

The coefficient, C, is dependent upon the point of cut-off, and upon the ratio of the lengths of stroke and connecting-rod. This ratio is usually about $\frac{2}{5}$; and assuming this figure, we have for C the following values:—

	POINT OF CUT-OFF IN FRACTIONS OF STROKE.				
	.10	.15	.20	.25	.33
C	241500	230000	218500	207000	184000

For electric-light engines the permissible variation in speed during the stroke should not exceed 1 or 2 per cent, hence the value of d is 50 to 100.

For engines with two cylinders, and having cranks at 90°, the weight of fly-wheel required is only about $\frac{1}{3}$ as much as in single-crank engines; and for three-cylinder engines with cranks at 120°, it is still less.

The strength of fly-wheels is a matter of serious importance, since a number of them have burst with disastrous results in electrical plants. These accidents, however, have been more frequent in electric-railway than in electric-lighting stations.

In the *Electrical World* of Oct. 21, 1893, p. 306, an account is given of the bursting of a fly-wheel of an engine in an electric-railway power-station in Brooklyn, New York. This wheel was 18 feet in diameter, and weighed about 20 tons. The station building was partly demolished; and some large fragments, weighing many hundred pounds, crushed through the roof of a house several hundred feet away, showing that the results are of a character nearly as serious and far-reaching as those of a boiler explosion.

Fly-wheels have usually been designed on a somewhat rough and incomplete theory of the straining-actions; and to balance the imperfection of the theory, very low working stresses have been assumed. But even this does not seem to secure safety. The ordinary calculations apply to the tension of the rim due to its centrifugal force and the bending of the arms caused by the acceleration or retardation of the rim, but proper allowance is

rarely made for the bending of the rim between the arms and other actions which occur.

If we consider the fly-wheel to be a simple ring of cast iron, and assume that the effect of centrifugal force is to slightly expand it uniformly in all directions, as indicated in Fig. 32, we have the expression: $f = .097\ v^2$, in which f is the tension in the rim in pounds per square inch, and v is the velocity of the center of the rim in feet per second.

In the case of fly-wheels having teeth or portions of the rim cut away for bolt-holes, etc., the centrifugal force will be practically the same as in a rim of uniform size having the same weight, but the strength will be less; and the expression then becomes, $f = \frac{A}{a}\ .097\ v^2$, in which A is the cross-section of a uniform rim of the same weight and diameter, and a is the actual cross-section at the weakest point. The arms or spokes of the wheel would apparently aid the rim in resisting centrifugal force; but actually their effect is often detrimental, since the rim tends to bulge out between the arms, as indicated in Fig. 33, and is thus subjected to a bending-stress in addition to the tension. This produces a stress which is usually considered to be fifty per cent more severe than the simple tension; but the effects are complicated, and difficult to determine exactly.

The arms are also subjected to a bending-strain due to variations in the velocity of the wheel. For example, the engine must bring the fly-wheel up to full speed in starting; and the acceleration tends to bend the arms, as represented by dotted lines in Fig. 34, assuming the direction of rotation to be right-handed. A similar effect is produced at the beginning of each stroke when the steam-pressure is greatest; and the arms tend to bend in the opposite direction at the end of the stroke when the pressure is much reduced by expansion. These effects are normal, and rarely serious; but much more severe stresses are produced by a short circuit, or the sudden putting on or taking off of heavy loads, and many authorities consider this to be one of the chief causes of fly-wheel accidents.

The greatest twisting force due to any or all causes which it is allowable for the shaft to transmit to the fly-wheel, or *vice versa* through the arms, is given by the formula: $T = nf_a\ Z$.

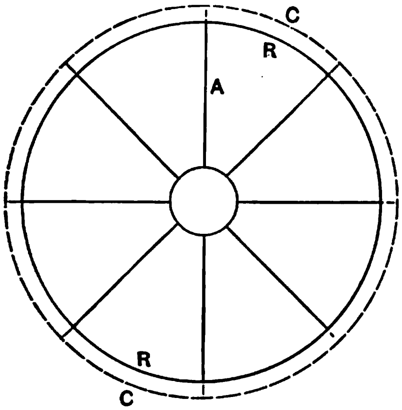


Fig. 32.

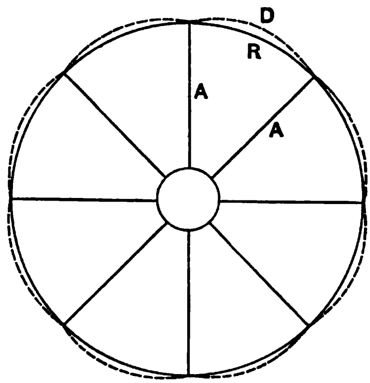


Fig. 33.

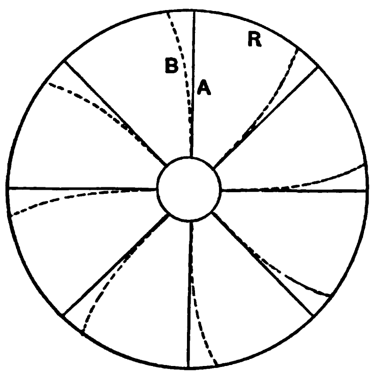


Fig. 34.

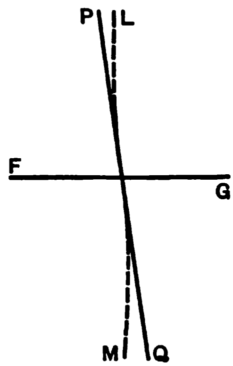
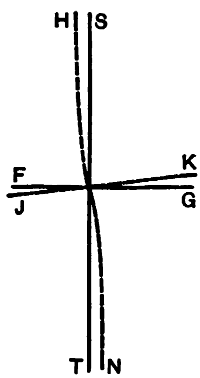


Fig. 35.



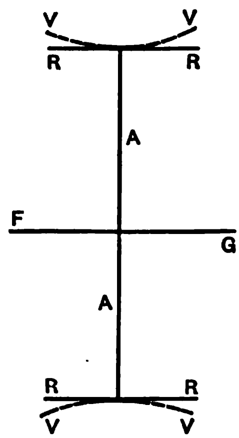


Fig. 36. *Strains in Fly-Wheels.* *Fig. 37.*

In this expression T is the maximum twisting movement between the shaft and the fly-wheel rim; n is the number of arms; f_a the safe stress per unit cross-section of the arm due to bending; and Z is the modulus of section of the arm. For a square $Z = \frac{1}{6} b^3$; for a rectangle $Z = \frac{1}{6} ba^2$; for an elliptical section of arm $Z = \frac{\pi}{32} ba^2$, in which a is the dimension of the arm in the plane of rotation, and b at right angles to it.

Another important cause of strains in fly-wheels is that arising from the fact that the plane of the wheel may not be perpendicular to the axis of rotation. It is often stated that this is a gyroscopic action, and that it tends to bend the rim back and forth; but both of these statements are erroneous. In Fig. 35, let FG represent the axis of rotation, and let PQ represent the plane of the fly-wheel, which in this case is improperly mounted upon the shaft, so that it is not perpendicular to the axis FG. When the wheel revolves, it tends to be bent into the form indicated by the dotted line LM; but there is no bending back and forth, since the point P always tends to be bent toward L, and every other point of the wheel always tends to be deflected in the same direction; that is, towards a plane perpendicular to the axis of rotation.

The only way in which there can be gyroscopic action is for the *axis* of rotation FG to be shifted through a certain angle into the position JK in Fig. 36. Then the fly-wheel rotating in the plane ST will strongly resist any deflection from this plane, and will therefore be bent into a form represented by the dotted line HN. If, now, the axis of rotation be brought back to its original position, FG, then the arms of the fly-wheel will be bent back and forth perpendicular to the plane of the wheel, producing a most severe effect. But such an action is not likely to occur, since it can only exist when the fly-wheel shaft swings, as for example, on board ship, or because the bearings are worn too large, thus allowing the shaft to move in them, or because they are not securely held, and therefore shift their positions; either of the two latter should be corrected as soon as it appears, and before any harm can result.

Another stress to which the fly-wheels are subjected is represented in Fig. 37, in which FG is the axis and AA the plane of

rotation, *rr* being the rim, which is assumed to be wide and thin. The effect of centrifugal force is to bend the rim into the form *VV*, which adds another bending-force to that shown in Fig. 33, in addition to the simple tension (Fig. 32) of the rim. This trouble may be avoided by making the rim thicker and not so wide, which would not appreciably reduce the moment of inertia; or in case the rim must be made wide, to carry a large belt, it should be supported by two sets of arms, this being a common construction.

It is thought by many engineers that fly-wheels are often ruptured by the actual crushing in of the rim, due to the pressure of the belt in case of a sudden short circuit or overload. It is doubtful, however, if this inward pressure is likely to crush the rim except under most extraordinary conditions; since it is opposed by the centrifugal force, and the rim of the wheel would act as an arch, with great strength to resist any forces directed inward, particularly if they are distributed. A joint or thick spot in the belt would tend to strike the rim a severe blow, and this might break it, especially if aggravated by a short circuit; and of course if the rim be broken at one point the entire wheel would go to pieces. The danger can be avoided by making the rim of considerable radial thickness, and by increasing the number of arms. In some cases the receiving-pulley on the dynamo or line-shaft appears to have yielded in this way, such pulleys usually being made with rather thin rims; and the breaking of the receiving-pulley has caused the failure of the fly-wheel from which it is driven. This might occur either by a fragment being thrown or being carried by the belt against the fly-wheel.

Construction of Fly-Wheels. — In view of the somewhat complicated strains in fly-wheels, and the frequency as well as seriousness of accidents, it behooves the engineer to exercise the greatest possible care in regard to their design, construction, and operation.

The usual practice is to allow not more than 1,000 lbs. per square-inch tension in cast iron, and 5,000 in wrought iron, and to keep the tangential velocity of a cast-iron rim below 100 feet per second. These figures would seem to be amply safe, the factor of safety being considerably greater than is used in most other cases; nevertheless, accidents often occur even with these precautions.

In the accident already cited, which occurred in Brooklyn, the normal velocity of the fly-wheel was only 85.87 feet per second; but this speed must have been far exceeded when the accident occurred, as a much higher initial velocity would be required to carry the fragments to the distances at which they were found. In fact, excessive speed, due to failure of the governor or other cause, is undoubtedly the cause of many fly-wheel accidents; and some arrangement for shutting off the steam in case the engine begins to race is desirable. This may consist of a centrifugal device which automatically closes the throttle-valve by means of a mechanical or electrical connection when the speed rises above the normal. One simple and effective arrangement of this kind comprises an electric motor connected by worm-gearing to an auxiliary throttle-valve. The current for working the motor is obtained from the main circuits of the plant, or from a special dynamo of about one horse-power, the motor being about one-half horse-power. When the circuit which operates the motor is closed, the latter immediately shuts the valve. The closing of the circuit may be effected automatically by a contact device on the governors; and the circuit may also be led to various convenient points, so that it can be closed by hand if the speed becomes excessive. Abnormally high speed, however, will not account for many cases of fly-wheel accidents in which the speed does not seem to have been much above its ordinary value. Moreover, the velocity which is usually allowed is so far below that apparently required to produce rupture, that the speed might be doubled, or even quadrupled, before the actual breaking should take place.

The fact that a cast-iron wheel is likely to have considerable *initial strains*, due to unequal contraction in cooling from the molten state, is probably the reason for the bursting of some wheels which have failed with only a slight increase above normal speed. To avoid or reduce these initial strains, the wheel may be built up of sections which are bolted together, instead of being made of one large casting, in which latter the initial strains may be so great that there is little margin of strength left to resist the centrifugal force.

Another method that has been employed to strengthen cast-iron fly-wheels consists in winding iron or steel wire around the

rim, with sufficient tension to greatly increase its resistance to bursting.

The use of cast steel instead of cast iron for fly-wheels would augment their strength from two to four times; but the cost would also be considerably increased, and would usually be thought excessive. Nevertheless, the higher cost is far less objectionable than danger of bursting. A wooden fly-wheel was made to replace a cast-iron one that burst at the Amoskeag Mills, Manchester, N.H., in 1891. The rim is built up of ash plank arranged to break joints, and fastened together by lag-screws, and also by through bolts. This is claimed to be stronger than a cast-iron fly-wheel; but it would hardly seem that it is the best construction, particularly when we consider that the arms are of cast iron, bolted to the hub and rim, and that the total weight of the wheel is 52 tons, of which only 16 tons are in the rim.

A radical departure from ordinary practice in fly-wheel construction is that used for driving dynamos in the station of the Union Railroad Company of Providence, R. I. (*Power*, April, 1894). This wheel has no arms, but consists of a hub, disk, and rim. The hub is made of cast iron, but the rim and disk are entirely composed of wrought-iron plates riveted together, the total weight being about 40 tons. This construction is expensive, but very strong, and should insure safety at any reasonable speed.

A very complete discussion of fly-wheel theory, construction, and accidents is contained in the issues of *The Electrical World* during October and November, 1894, to which contributions were made by twenty or thirty engineers, including many of the most eminent authorities on the subject.

It has been proposed * to use fly-wheels of considerable weight at high speed to store energy. This might be advantageous for the rapid fluctuations of load in electric railway work, but would not be of much value for the slow variations in electric lighting.

Principles of Condensing-Engines. — Almost any steam-engine can be converted into a condensing one by connecting to it an apparatus in which the steam is cooled and condensed after

* "Possibilities of Securing better Regulation at Central Light and Power Stations by Means of Fly-Wheel Accumulators," a paper read by John Galt before Canadian Electrical Society, September, 1894.

leaving the cylinder instead of being allowed to escape directly into the atmosphere. The advantage obtained is a reduction of the back pressure from that of the atmosphere, which is about 15 lbs. per square inch, down to about 2 to 5 lbs. per square inch, which is as near a perfect vacuum as can be practically maintained in a condenser. Condensation has practically the effect of raising the steam-pressure, since the difference in pressure on the two sides of the piston is augmented about 10 lbs. per square-inch, producing a corresponding increase in the power of the engine. Since this additional effective pressure is gained without drawing any more steam from the boiler, it follows that the efficiency of a condensing-engine is higher, other things being equal. This might also be proved by the fact that the difference between the initial and final temperatures of the steam is increased. (See page 91.)

Condensing-engines are not always desirable, however, since in some cases the disadvantages more than offset the gain. For example, in a small plant the cost as well as increased complication of the condenser and pumps would more than counterbalance the slight saving in back pressure. In a simple (i.e. non-compound) engine it is not desirable to have a great range of temperature because of cylinder losses (page 52), the usual extreme differences in pressure not being more than 80 to 100 lbs.; hence if the steam-pressure has this value it may not be desirable to increase its range by adding a condenser. Moreover, it would probably be easier and cheaper to design the boiler for a higher pressure than to have the complication of a condenser.

This applies to comparatively low pressures of say 80 to 100 lbs.; but if the pressure is already very high, that is, 150 or 200 lbs., then of course it is possible to obtain about 10 lbs. more effective pressure by the use of a condenser without increased danger. The gain, however, is not a very large percentage in the case of such high pressures.

The original reason for using a condenser was the fact that very low steam-pressures were the rule, 15 lbs. being considered high in the time of Watt about one hundred years ago. With this pressure the addition of the condenser greatly increased the power obtained from a given size of cylinder and quantity of steam. But at the present time no one would think of using

less than 80 lbs. pressure in an electric-lighting plant, and for large central stations 125 to 150 lbs. is common; consequently, the additional effective pressure gained by condensation is a very small percentage of the boiler pressure, but it adds materially to the power and efficiency, as explained in Chapter XII.

There are two radically different types of condenser, — the jet and the surface condenser.

The jet condenser is the original form, having been employed by Watt, and consists of a chamber into which the exhaust steam and a jet of cool water are conveyed, the former being condensed by actually mixing with the latter. The volume of the chamber is ordinarily from one-third to one-half that of the cylinder of the engine.

Forms of jet condenser are made by the manufacturers of steam-pumps, such as the Blake, Worthington, Knowles, and others. The Blake vertical type, shown in Fig. 38, consists of a condensing-chamber, combined with steam-cylinders which operate the two pumps, — one to deliver the jet of water to the chamber, and the other to remove the air from it. The jet condenser is used where the condensed water is not returned to the boiler. The steam takes up oil in the cylinder which may be objectionable in the boiler (see page 113). This type is also used with salt or very impure condensing-water (in land practice), because it is more easily cleaned than the surface type. A condenser operated by its own steam-cylinder is called *independent*, and is generally preferable to those in which the pumps are connected to and worked by the moving parts of the engine, because the condenser may be started up before the engine, or separately controlled in any way that may be desired.

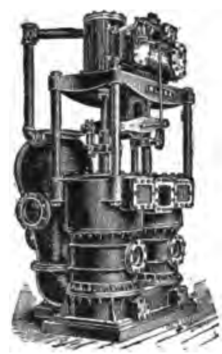


Fig. 38.
Blake Jet Condenser.

The surface-condenser differs from the foregoing in the fact that the exhaust-steam is not mixed nor brought in actual contact with the water which condenses it. In the surface-condenser the steam is separated from the cool water by metallic partitions or tubes, the ordinary arrangement being to pass the cool water through brass tubes around which the steam is caused to circu-

late, or *vice versa.* The condensing-surface required is usually from 1½ to 3 square feet per indicated horse-power.

The Wheeler condenser is a standard form of surface-con-

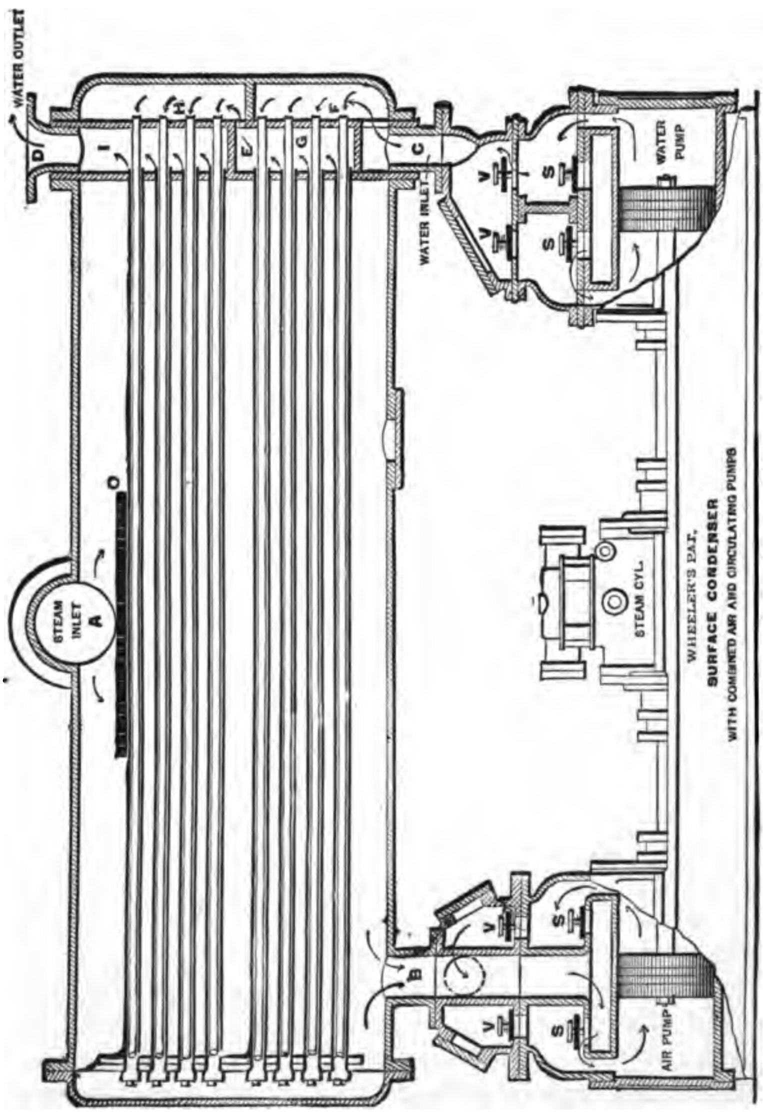


Fig. 39. Section of the Wheeler Surface Condenser.

denser. Fig. 39 represents a section of this apparatus in which the exhaust-steam from the engine enters the condenser by the nozzle *A*, and comes in contact with the perforated scattering-

plate O, which protects the tubes from the direct impingement of the steam. The condensed steam gravitates to the bottom of the condenser, and flows through the outlet B to the air-pump, which discharges it through a pipe represented by a dotted circle in the figure. The circulating-pump on the right forces the cooling water through the inlet C into the compartment F, from which it passes into the small tubes as indicated. After traversing the small tubes, the water returns through the annular spaces between these tubes and the large tubes which surround them, and empties into the compartment G; thence it flows through the passage E into the compartment H. The water then circulates in a similar manner through the tubes of the upper section, and finally discharges through the outlet D. Both the air-pump and circulating-pump are operated by a single direct-acting steam-cylinder, as shown. The tubes are arranged to be easily unscrewed and removed for cleaning or repairs.

Water for Condensation. — The obtaining of a sufficient supply of water for this purpose is often a difficult matter, and should be considered in locating the station, as stated in Chapter V. The quantity of condensing-water required depends upon its temperature, but it is ordinarily estimated to be from 50 to 75 times the weight of water evaporated in the boiler; hence it takes about 1,000 to 2,000 lbs. per horse-power for each hour that the engine is working. This amount is so large that it is evident that condensing-engines cannot be used unless an almost unlimited supply is available, such as that afforded by a river or other large natural body of water. The waterworks of a city, for example, could not be expected to furnish condensing-water, no matter how ample the supply might be, and in any case the water-tax would be prohibitive. It is possible to use water for condensing which is far less pure than that required in the boiler, particularly if surface-condensers be adopted, and in many cases salt water is employed for the condensers of electric-light stations where these are located on the seashore or on an arm of the sea. It is, nevertheless, very undesirable even for condensing-water to contain salts or dirt, since they clog and interfere with the working of the condenser and pumps. For this reason condensing-engines are not used in some cases where an abundant but impure supply of water is at hand; and in other instances a large well is

dug to obtain the condensing-water, even when the station is close to the shore.

The large station of the Internationale Elektricitäts Gesellschaft of Vienna is situated on the bank of the Danube; but the water for condensation is taken from a well, in order to avoid the dirt of the river-water.

If the natural supply of water is not sufficient, the plan is sometimes adopted of using the water over and over again, the arrangement being such that it is kept cool by evaporation and exposure to the air in a number of large, shallow pans through which it flows successively.

Principles of Compound Engines. — In the compound engine the steam partially expands in one cylinder, and then passes to another cylinder, in which it completes its expansion. At first sight it is difficult to see any advantage in thus subdividing the expansion and work of the steam, since the efficiency and total capacity of a steam-engine to do work depend upon the initial and final temperatures of the steam, and would seem to be entirely independent of whether the expansion all takes place in one cylinder or not. As a matter of fact, this would be true if the walls of the cylinder did not take up and give out heat to the steam at different parts of the stroke, causing serious losses and modifications in the action of the steam in the cylinder.

For example, let us assume that the steam enters the cylinder at a pressure of 100 lbs. above that of the atmosphere, which corresponds to a temperature of 170° C., and that it leaves the cylinder at the atmospheric pressure which corresponds to 100° C. Thus the change in the temperature of the steam during each stroke is 70°, and if the internal surface of the cylinder is cooled down to 110° by the heat taken from it by the exhaust-steam, then the incoming steam at the next stroke will find the cylinder to be 60° below its own temperature, and it will therefore give up a great deal of its heat to the cylinder by radiation as well as by actual contact. Steam, unfortunately, has considerable power either to give out or to absorb heat, and results show that the losses in the cylinder from this cause are very serious. It might be thought that the heat returned to the steam by the cylinder during the latter part of the stroke would counterbalance the loss in the beginning; but most of the heat given

back to the steam passes away in the exhaust, since the latter is in contact with the cylinder during the entire back stroke.

The reason for the loss may also be understood if we consider that the effect of this giving and taking of heat is to reduce the initial temperature and increase the final temperature of the steam, and the efficiency is directly dependent upon the difference between these two temperatures. (Page 91.)

The trouble is further aggravated by the fact that the steam is usually "wet;" i.e., is slightly condensed when it enters the cylinder, and becomes still more so by the act of expansion, even though it did not give up any of its heat to the cylinder. Hence the aggregate effect due to all these causes produces a very considerable condensation and diminution of pressure, and is one of the chief sources of trouble and loss in the action of the steam-engine. The most evident way to mitigate this difficulty would be to *superheat* the steam; that is, raise its temperature above the saturation point after it has left the boiler, so that it is capable of losing heat in the cylinder and still remain uncondensed. This plan has been continually advocated from the time of Watt to the present day; but, as a matter of fact, it is rarely adopted, owing to the complication and practical difficulties which it involves. Its advantages are so great, however, that it would seem as if it ought to be developed and accepted generally. The method of superheating steam by introducing hot air at 553° F. into the cylinder and jacket has been tried by Professor Andrew Jamieson, who obtained good results.*

Another way to diminish the cylinder losses is to adopt high speed, and thus reduce the time during which the steam can transfer its heat to the cylinder. It is generally stated by authorities that cylinder condensation varies approximately as the square root of the time of action,† other things being equal. This is one of the advantages of the many types of high-speed engines now employed in electric lighting. But the most successful method of reducing cylinder losses is that of multiple expansion as obtained in compound or triple expansion engines. To appreciate the advantage of this method let us take the same case as before — an initial pressure of 100 lbs., and a final pressure of

* *Electrical World*, July 20, 1895.

† Thurston's *Manual of the Steam-Engine*, Part II., page 702.

that of the atmosphere, but assume that the steam expands from 100 lbs. pressure down to 40 lbs. in one cylinder, and then passes to another cylinder, in which it completes its expansion. The initial temperature is 170° C., as before, but it only falls to 141.5° (which corresponds to 40 lbs. pressure) in the first cylinder, in which the total range is therefore only 28.5°, and the incoming steam is only 18.5° above the temperature of the surface of the cylinder, assuming, as before, the later to be 10° above the steam which leaves it. Similarly in the second cylinder the total range is 41.5°, and the cylinder would be 31.5° cooler than the steam which enters it.

Thus it appears that the maximum and average differences in temperature between the steam and the cylinder walls in the compound engine would be less than half as great as those in the single cylinder. A triple-expansion engine in which the steam is successively expanded in three cylinders would have about one-third the range of temperature in each cylinder that would occur in a simple engine having the same initial and final pressures, and the losses would be still further reduced. To offset the advantage obtained by dividing the expansion between two or more cylinders, there is the fact that the total internal surface of the two cylinders of a compound engine would be greater than that of a single cylinder, and the time during which the steam can transfer its heat to the cylinder is also greater, other things being equal.

But the results of general experience and actual tests show a decided economy secured by the use of compound engines in place of simple engines; and triple and quadruple expansion engines show a still further saving in fuel consumption, provided the size and importance of the plant warrant the increased cost, complication, and care which multiple expansion involves. But it should be remembered that a great deal of the higher efficiency often credited to compound and triple expansion engines is due to the *increased steam-pressure* which is applied to them.* This in itself gives higher economy even in a simple engine; and while it is decidedly preferable to adopt multiple expansion with high steam-pressures, nevertheless high pressure can be used, and will increase the efficiency even in a simple engine. For example, a locomotive requires less coal at 175 lbs. pressure than it

* See page 77.

does at 150 lbs. to give the same power, even though it is a simple, and not a compound, engine.

Besides the economy of the compound engine in reducing cylinder condensation, it also has advantages in distributing the strains and work of the engine between two cylinders instead of one; and if the cranks operated by the two cylinders are set at right angles to one another, then the rotational effect is more uniform, and the engine will not catch on the dead center in starting.

The only essential advantage, however, of compound engines is the reduction of the range of temperature in any one cylinder; and if some practical means were devised to prevent the cylinder from absorbing heat from the steam, it is very doubtful if compound engines would be used to any great extent.

For example, it has been attempted to line the cylinder with bismuth, lead, or some alloy which is a poor conductor of heat and also has a low specific heat; but these materials are not sufficiently strong or durable for the purpose. Dr. Charles E. Emery lined the whole interior of the cylinder with glass or porcelain, but without permanent success.* The use of plenty of oil in the cylinder, or coating the interior with varnish, both tend to reduce cylinder condensation.† This matter has also been investigated by Mr. Croll.‡ It is certainly to be hoped that some such method to reduce cylinder condensation may be made practicable.

The subject of condensing and multiple-expansion engines, particularly the effect upon them of variable loads, is discussed in Chapter XII.

The typical forms of compound and triple expansion engines used in actual practice are described in the following chapter.

* *Trans. Am. Soc. Mech. Engs.*, 1881.

† Thurston's *Manual of the Steam-Engine*, Part II., page 704.

‡ *London Electrical Review*, Oct. 4, 1895, p. 416.

CHAPTER XI.

TYPICAL FORMS OF STEAM-ENGINE FOR ELECTRIC LIGHTING.

HAVING considered the general principles and construction of steam-engines, let us now examine the most important types used in electric lighting. These may be grouped in four general classes: —

1. Large, *low-speed* engines of the Corliss or similar type, usually running at 50 to 125 revolutions per minute.

2. Small and medium-sized *high-speed* engines running at 200 to 400 revolutions per minute.

3. A sort of compromise between the two foregoing, which has been developed for direct coupling with dynamos. These are usually vertical and compound or triple expansion, being of the so-called "marine type." If these are large, they approximate class 1; if they are small, they resemble class 2. Their speed is usually between 125 and 200 revolutions per minute.

4. Steam turbines of enormously high speed, running at 3,000 to 25,000 revolutions per minute.

Other peculiar steam-engines, such as oscillating and rotary types, have been tried or proposed; but they have not been used to a sufficient extent to warrant much attention being given to them.

Corliss Engines. — The most successfully and extensively used stationary engines are of the type devised by George W. Corliss of Providence, R.I., in 1849. The principal features of this engine are the subdividing of the valve functions and the automatic cut-off, by which the admission of steam to the cylinder is controlled by the governor, so that the point of cut-off varies in proportion to the load. Many modified forms and improvements in detail have been brought out; but the Corliss valve-gear remains substantially the same in its general construction and action. At first sight it might appear to be a complicated and somewhat clumsy mechanism; but its long-continued and almost

universal success; and the fact that in the last few years there is a tendency to revert to it, rather than to depart from it, is a conclusive proof of its great merit. Its great advantages are correct steam distribution and small clearance space.

A standard form of Corliss engine is shown in Fig. 42, and a skeleton view of the valve-gear in Fig. 40. There are four separate valves, two to admit the steam to the cylinder, and two others to let it out after it has been used. These valves are of the rotary type; that is, they turn slightly about their axes, being made in the form of slightly tapering cones, and having

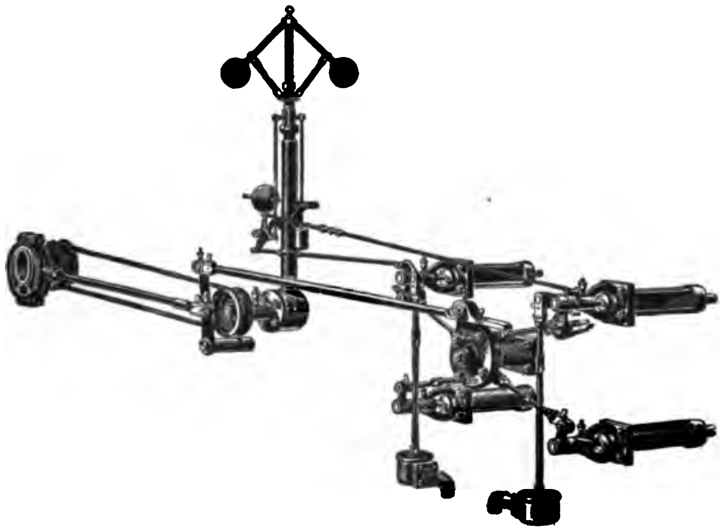


Fig. 40. Skeleton View of Corliss Valve-Gear.

the steam-ways cut in them as longitudinal slots. It is evident that a valve of this sort can be opened or closed very quickly. The valves are usually made separately adjustable, not only in the extent of their motion, but also in their position at any given instant. All four valves are connected to and driven by a "wrist-plate," which is pivoted on a pin projecting from the center of the cylinder. This wrist-plate is caused to oscillate through a certain angle by the eccentric on the shaft.

The exhaust-valves (the lower ones in Fig. 40) are opened and closed by the eccentric, and the admission-valves (the upper

ones) are also opened by it, but they are detached and closed by gravity, or by vacuum pots. The action of the wrist-plate is to cause a very sudden opening or closing of the valve. This action is evident from Fig. 41, which shows that a slight angular motion of the wrist-plate *W* from *A* to *B* opens the valve *V* almost to its full extent; and the further turning of the wrist-plate to *C*, although equal in amount, has the effect of holding the valve open with only a very slight movement. This motion is precisely what is required in a steam-engine valve, and the perfection and ingenuity of this feature of the Corliss gear probably have much to do with its success. The dropping of the admission valves and cutting off of the steam is accomplished by providing the links leading to the steam-valves with catches, which are disengaged at a certain point and allow the valves to close, but they take hold again on their

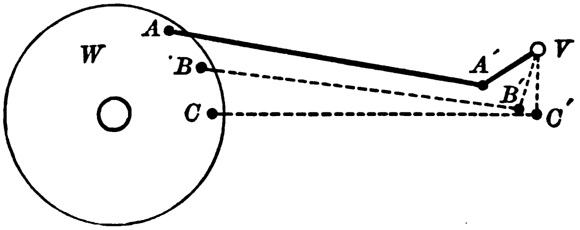


Fig. 41. Motion of Corliss Wrist-plate and Valve.

backward stroke and reopen the valves. The position of these catches is controlled by rods connected to an ordinary centrifugal governor, as shown in Fig. 40, so that the valves are released and closed at a certain fraction of the stroke corresponding to the speed and load. The governor can cause the cut-off to occur at any point, from the beginning up to nearly half of the full stroke, which gives a wide range in the power of the engine.

The Corliss valve-gear is ordinarily applied to engines of comparatively low speed of from 50 to 100 revolutions per minute; but it is now being used in many cases at 125, and it is claimed that it can be worked up to 140 revolutions per minute. But it is evident that this or any other form of cut-off which is not positive in its action is not suited to high-speed engines, and some form of shaft-governor or similar device is usually adopted. There are a number of excellent forms of the Corliss type of engine

made in America and Europe. One of the largest and most interesting examples of these engines was that shown at the Chicago Exposition of 1893. This engine was quadruple expansion of 2,500 horse-power, and had four cylinders of 72 inches stroke each, and of diameters of 26, 40, 60, and 70 inches respectively. This engine was employed to drive two large Westinghouse dynamos, each of 750 kilowatts capacity, for lighting the grounds and buildings. There are many types of Corliss engines made

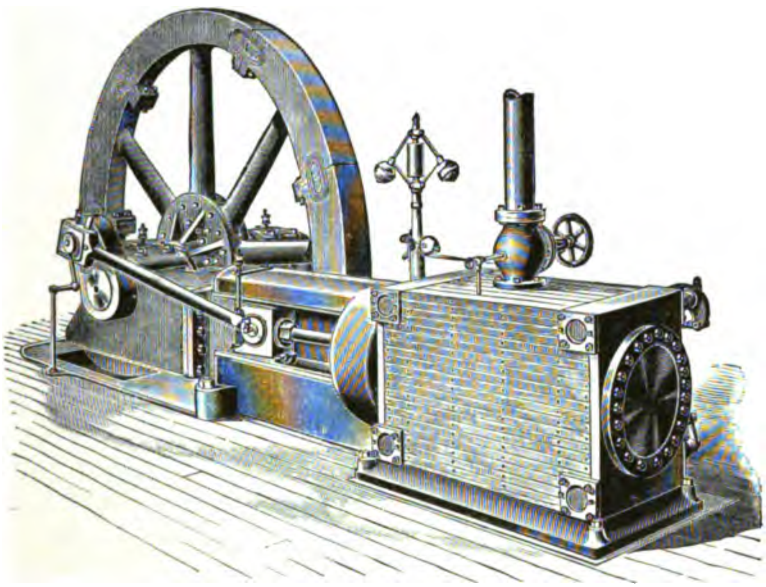


Fig. 42. Corliss Engine.

by various manufacturers; these are usually similar in general appearance and design, but differ in details of construction. One typical form of Corliss engine is shown in Fig. 42.

The engines used in the stations of the Allgemeine Elektricitäts Gesellschaft in Berlin, are interesting examples of the Corliss type. They are vertical tandem-compound engines of 1,000 actual horse-power each, directly coupled to two dynamos, one on each end of the shaft, and running at 68 revolutions per minute. Both cylinders of these engines are provided with the regular Corliss valve-gear. The engines are built by Van der Kerchove of Ghent, Belgium.

The Greene Engine is another successful type of low-speed engine. It has four valves, two for steam and two for exhaust, as in Corliss engines; but the valve-gear is quite different, and gives even greater independence of action of the steam and exhaust.

High-Speed Engines. — *The automatic cut-off high-speed type* of engine is especially interesting and important in connection with electric lighting; in fact, the development and extensive use of these engines are almost entirely due to their application to this purpose. The distinguishing feature of this type consists in the placing of the governor upon the main shaft or fly-wheel, and connecting it directly with the eccentric, so as to control its action, and vary the point of cut-off of the valve. This location of the governor is made possible by the fact that these engines are of sufficiently high speed to give the necessary centrifugal force to insure the proper action of the governor; whereas the governor of a low-speed engine is mounted on an independent spindle at some distance from the main shaft, and connected to it by belting or gearing, to obtain the necessary speed of rotation.

In Corliss and other detachable or "drop" cut-off engines, and also in cam-motion valve-gear, the speed is limited by the fact that the cut-off is not rapid enough with respect to it, hence some *positive* cut-off is required in high-speed engines. This usually consists in directly connecting the cut-off device with the eccentric, so that the latter is forced to operate. The direct connection between the governor and valve-gear is a great advantage of the high-speed type in many ways, and secures compactness, as well as quickness and effectiveness of regulation. When the dynamo first came into general use for electric lighting and other purposes, this type of engine was already in existence, but not in a very perfect form. The dynamos then used were of comparatively small size of from 10 to 50 horse-power, and ran at high speeds approximating two thousand revolutions per minute.

This immediately created a demand for a steam-engine of similar power which could be connected to the dynamo by belting, and give the necessary speed without the use of a counter-shaft. Nearly perfect constancy in speed was also required; and in that respect nearly all types of engines were at that time quite deficient. In almost any kind of work except electric lighting, a varia-

tion of 5, or even 10 per cent, in speed is not very objectionable; whereas, for incandescent lighting a variation of more than 1 or 2 per cent is not considered allowable. This had the effect of greatly improving the perfection and rapidity in the governing-action of steam-engines. Another advantage of the high-speed engine is the fact that owing to rapidity of the motion, there is far less fluctuation in the light of the lamps caused by the variation in speed as the crank passes the dead center. This is extremely objectionable, and is often quite perceptible in a low-speed engine unless the fly-wheel is very large and heavy.

This new type of engine, which seemed so admirably suited to its purpose, was used almost exclusively for driving dynamos from its original introduction up to within a few years, resulting in great improvement and multiplication of forms. The use of electricity on a larger scale, however, and the consequent increase in the size of dynamos, have demanded the introduction of very large steam-engines and dynamos, in many cases directly coupled together. Large engines are necessarily of lower speed, and essentially different from the high-speed engines of smaller size. The high-speed engines are not usually of such high economy as the Corliss, for example; and the wear and tear, attendance and lubrication required by the high-speed has had the effect of somewhat diminishing their popularity. They are still, however, and probably will continue to be, commonly employed for smaller installations, whether isolated plants or central stations. Compactness, close regulation, convenience of connection by direct coupling, or by belting without counter-shafting, and avoidance of flickering in the lamps as stated above, are all distinct and important advantages which these engines possess, and which make them in many cases the most desirable form to select. Engines of this type of larger size, usually compound or triple expansion, are being brought out by various manufacturers, and will tend to increase the economy, scope, and usefulness of this very important class of engines. There are so many excellent forms of high-speed engines in the market that it would be impossible to describe, or even to enumerate, all of them; but certain common and standard types are here given as examples.

The Armington & Sims Engine has been extensively employed for driving dynamos in central stations and isolated plants from

the first installations up to the present time. For many years it was the standard engine adopted in the Edison as well as other stations and plants. The introduction of other similar forms and the demand for larger units have somewhat modified this practice at present, and various types are being substituted in many cases. The general form of this and other makes of high-speed engine is shown in Fig. 43. It is provided with two pulleys, one on each side, and is therefore constructed with a "center crank" working between "double disks." This form is used where two dynamos are driven from one engine, which is a very common practice; but

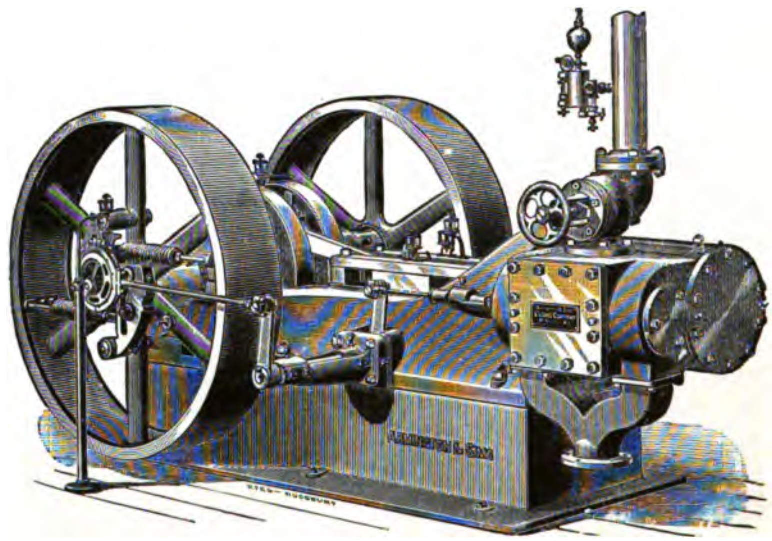


Fig. 43. The Armington & Sims Engine.

it has the disadvantage that the crank and connecting-rod end are quite inaccessible in the narrow space between the two disks, and are therefore somewhat difficult to adjust or repair. For cases where only a single pulley is required, the single-disk type of engine is made by this as well as by other manufacturers.

The forms of valve and governor employed in the Armington & Sims engine are its chief characteristics. The cylinder and valve are shown in section in Fig. 44. The valve is of the piston type, and is made hollow, so that the steam enters the cylinder by two paths, as represented by arrows, which facilitates the taking of steam promptly at the beginning of the stroke. For the same

reason the cut-off is more sudden and definite. The governor (Fig. 45) consists of two weights 1, 1, pivoted on the spokes of the wheel which is fixed to the engine-shaft; each weight is controlled by a spiral spring, one end of which is attached to the weight and the other end to the spokes or rim of the wheel. There are two eccentrics, *C* and *D*, one within the other. The inner one, *C*, is mounted upon and turns freely on the shaft, and is provided with ears or projections to which the rods 2, 2, are connected; the other ends of the rods 2, 2, are connected

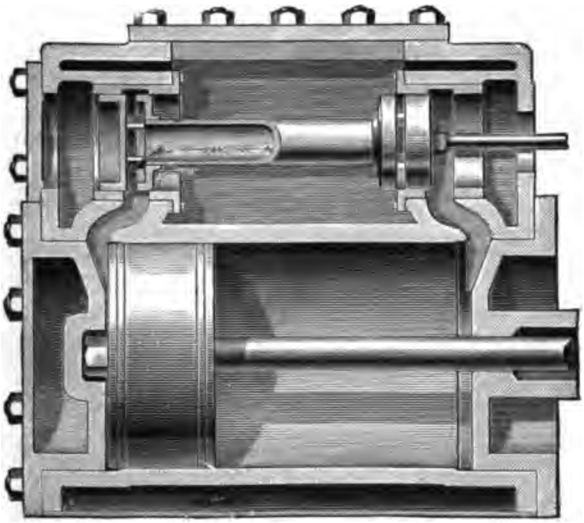


Fig. 44. The Cylinder and Valve.

to the weights 1, 1. The outer eccentric, *D*, is mounted upon and is free to turn on the inner eccentric, *C*. This outer eccentric is connected by a rod, 3, to the toe of one of the weights; on this outer eccentric, *D*, is placed the usual eccentric-straps connecting it to the valve-rod. To avoid confusion these are not shown in the figure.

When the engine is running at its highest speed, that is, with no load, the weights 1, 1, due to their centrifugal force overcoming the springs, will be out against the rim; and the eccentrics will be drawn by the rods into the position represented in Fig. 45, which gives the valve the least travel and earliest cut-off, the eccentricity of the two combined eccentrics being the distance *A*.

If we consider the other extreme, when the engine has its greatest load, and lowest speed, requiring latest cut-off, the weights will be in the innermost position, as shown in Fig. 46 ; the inner eccentric, *C*, having been moved back, and the outer eccentric, *D*, forward, this increases the combined eccentricity to the amount represented by the line *B*, and is sufficient to allow the steam to enter the cylinder for about seven-tenths of the stroke. The lead of the valve, and consequently the point of admission of the steam,

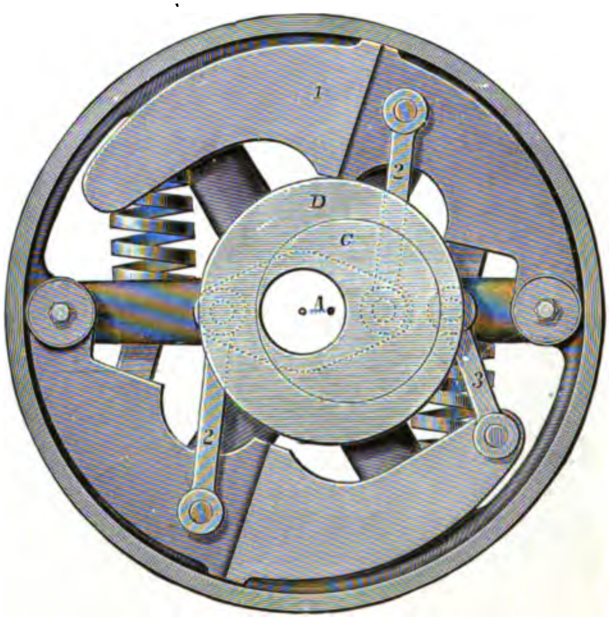


Fig. 45. Governor of Armington & Sims Engine.

remain practically constant for all positions of the eccentrics; but the throw or opening of the valve varies according to the speed and load of the engine, these results being secured by moving two eccentrics in opposite directions in the manner just described.

The chief criticism concerning this form of governor is the friction which is involved in turning the inner eccentric on the shaft and the outer eccentric upon the inner, which might cause the governor to fail to move with slight or gradual changes of speed.

In addition to the above simple and standard type, this engine

is also made in the tandem-compound form similar to that shown in Fig. 50; in the cross compound form similar to Fig. 47; and in the vertical form similar to Fig. 60.

The Ball Engine is another well-known type of high-speed engine. Its most distinctive features are in the valve and the governor.

The valve consists of two parts connected by a telescopic joint; this works as a double-faced slide-valve between two surfaces in which the ports are formed. The steam which is

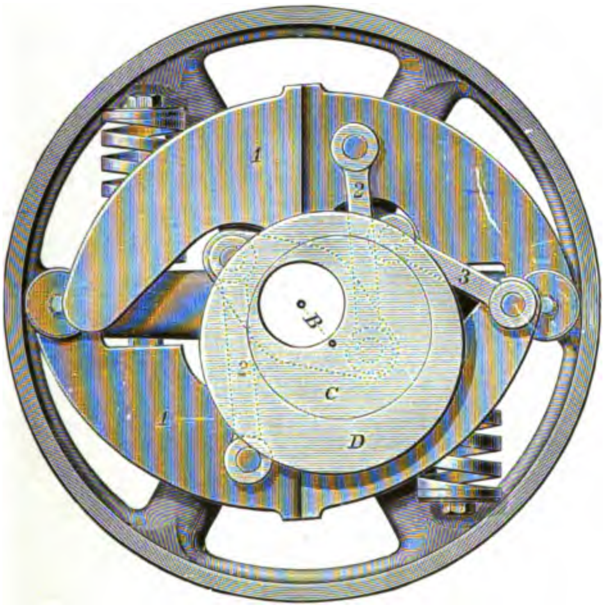


Fig. 46. Governor of Armington & Sims Engine.

admitted to the inside of the valve presses the two faces apart with respect to each other, and against the ports above and below. The object of this arrangement is to insure a steam-tight contact, and at the same time to allow for wear. The governor, which is represented in Fig. 48, consists of an eccentric connected by links to centrifugal weights which shift it when the speed rises or falls. The springs *DD*, which resist the centrifugal force, have full theoretical tension, so that they are only balanced at a certain speed, and any variation from this would cause them to move to one or the other limit of their path. This condition

is very sensitive, however, and would cause "hunting" of the governor, as already described (page 136), were it not for the supplementary spring *S*, which is connected to a dashpot *C*. When motion of the governor-weights takes place inward or outward, this spring *S* is compressed or extended for the moment, and gives stability to the governor; but almost immediately the slower motion of the dashpot allows the spring to return to its normal condition, in which it exerts no force. Hence the speed of the engine is determined by the springs *DD*, which are adjusted to almost perfect isochronism, and the dashpot, *C*, merely resists sudden disturbances; but at the same time the interposition of the spring *S* allows freedom and quick action of the governor. These engines are made in the standard single-cylinder form, similar in general appearance to Fig. 43, in eighteen sizes, from 20 to 300 horse-power, the speed of the former being 450, and of the latter 220, revolutions per minute. They are also made in the tandem compound type in nine sizes, from 60 to 400 horse-power, with speeds from 300 to 220 respectively, and in the cross compound form (Fig. 47) in eight sizes, from 100 to 600 horse-power, with speeds from 300 to 220 revolutions per minute.

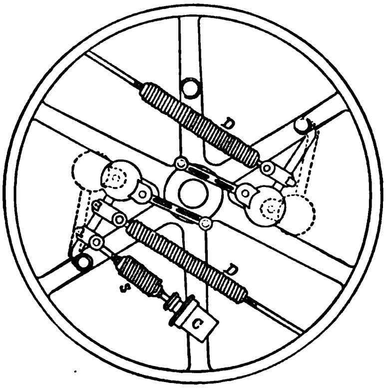


Fig. 48. Governor of Ball Engine.

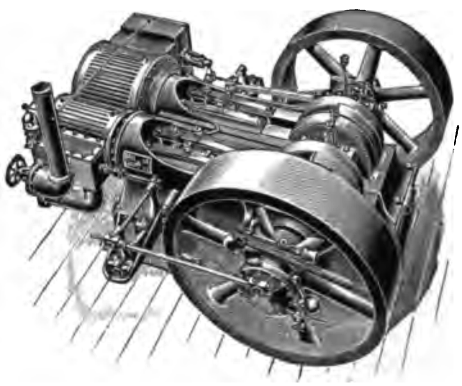


Fig. 47. The Ball Cross-Compound Engine.

The "Straight Line" Engine is a standard type of high-speed engine which embodies a number of characteristic features. The frame is cast in one piece with the cylinder and steam chests. It

is the same on both sides, and is straight from the cylinder to the main bearings, hence the name of the engine. The cylinder is arranged to have a boring-bar mounted in it, so that it can be re-bored when necessary, otherwise the entire frame and cylinder would have to be mounted in a lathe. The piston-rod packing is a simple Babbitt metal bushing, which rests in a spherical seat to allow self-alignment, being held in place by a gland and screw-cap. It is reamed to have a free sliding fit with the piston-rod, and its length is made about five times the diameter of the rod to prevent leakage. It is compressed by the screw-cap to take up the wear. The lower guide of the cross-head can be slightly

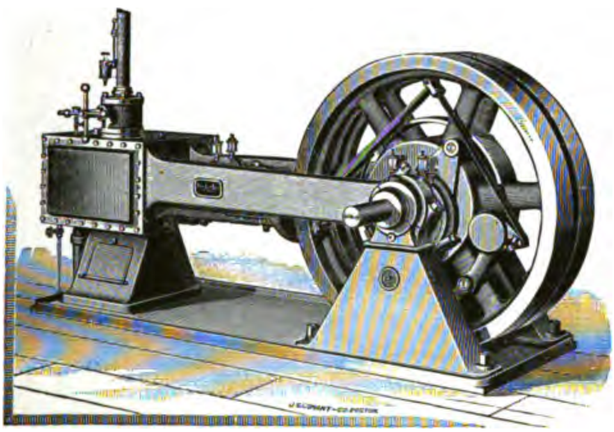


Fig. 49. "Straight-Line" Engine.

raised or lowered by a screw and inclined-plane adjustment to bring the piston-rod in perfect alignment. The main bearings have, in addition to oil cups, self-oiling rings similar to those used in dynamos. The governor consists of a single ball linked to the eccentric, and connected to a straight plate-spring by a metal strap as shown. The ball is hollow and loaded with lead which can be increased or decreased to vary the speed of the engine. The valve (Fig. 53) is a thin rectangular plate with five openings through it. It works within a space formed by the valve-seat and a pressure-plate. The latter rests against two distance-pieces, which relieve the valve from pressure. The distance-pieces can easily be reduced in thickness when the valve wears. The pressure-plate has recesses opposite the ports in the valve-

seat, thus giving double ports for steam admission and exhaust. These engines are made in six sizes, from about 30 to 200 horse-power, with speeds between 300 and 200 revolutions per minute.

The McIntosh and Seymour Engine is another type largely used for electric light and power purposes. The shaft-governor is similar in general action to those already described, but contains several distinctive elements. The centrifugal force of the governor-weights are resisted by a double plate spring, as shown in Fig. 50. This spring acts upon each weight through a steel pin, both ends of which rest in hard steel cups. The sensitiveness of the governor can be adjusted by changing the length of these pins between the weights and the spring, the pins being arranged with a screw adjustment for this purpose.

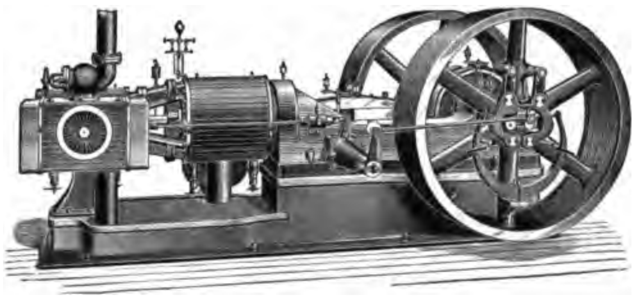


Fig. 50. McIntosh & Seymour Tandem-Compound Engine.

The speed is regulated by changing the weight of bushings placed in holes in the centrifugal weights. The eccentric is carried on a pendulum, which allows it to swing across the shaft and thus change the throw of the valve. This pendulum is moved by jaws on the weights inclined at such an angle that, while the movement of the weights easily controls the position of the pendulum, the reverse is not true, and the weights are free from the disturbing influence of the push and pull of the valve.

The valve is of the piston form, and works in a valve-seat which is split, and can be contracted by the adjusting-screw shown in Fig. 51. This split ring, which forms the valve-seat, is made tapering towards the edges, so that it tends to preserve a perfect circle even when contracted. This enables the fit of the valve to be perfectly adjusted at any time in order to take up the

wear and avoid leakage. The leaking of a piston-valve after it is worn, and the difficulty of refitting it, have always been urged against it as serious objections. On some of the larger McIntosh and Seymour engines a form of gridiron valve is used, which is claimed to have even less clearance than a Corliss engine; for example, in a 36 × 48 inch cylinder, the clearance is only $2\frac{1}{4}$ per cent. These valves are opened and closed rapidly by means of a toggle motion, but when closed remain practically stationary, thus saving friction, at the same time securing a quick opening and closing. (Fig. 52.)

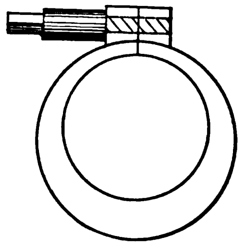


Fig. 51.
Adjustable Valve-Seat.

The ordinary horizontal single-cylinder form of this engine is made in twenty sizes, from 22 to 500 horse-power, with speeds from 320 to 175 revolutions per minute respectively. Numerous sizes of tandem-compound high-speed engines of this type, shown in Fig. 51, are also built, the power ranging from 65 to 500 horse-power, and speed from 275 to 175 revolutions per minute.

Larger engines of from 300 to 2,000 horse-power are also made in the side-crank type (Fig. 52). Similar sizes of vertical engine

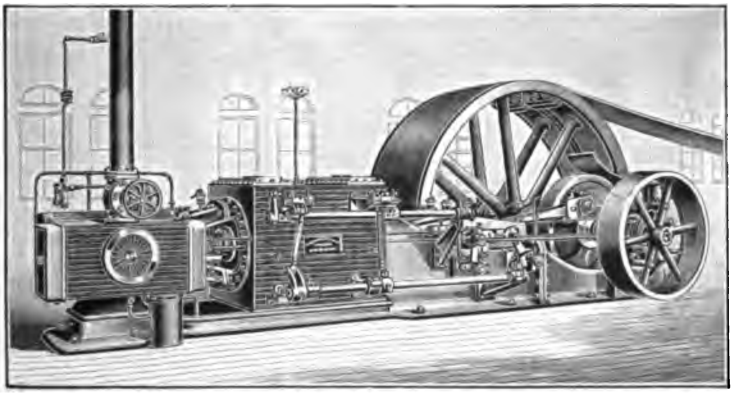


Fig. 52. Large Type of McIntosh & Seymour Engine.

are also made; but both of these two latter styles belong more to the second or medium-speed class of engines, described on page 179, than to the high-speed type.

The "Ideal" Engine is often selected for electric-lighting plants, owing to its general merits, and the fact that the working parts are completely inclosed in a cast-iron case. This arrangement makes the engine self-lubricating ; since the supply of oil which is kept in the bottom of the case is thrown about by the motion of the crank-pin, thereby drenching the working-parts with lubricant as represented. Special channels are also provided to catch the oil, and convey it to points which it would not reach directly. For example, there is one at the extreme end of the casing; this supplies the main bearings with a constant flow of oil. The governor is of simple form, consisting of an eccentric mounted as a pendulum on the fly-wheel, so that it is moved across the shaft by centrifugal weights, resisted by springs, and moderated

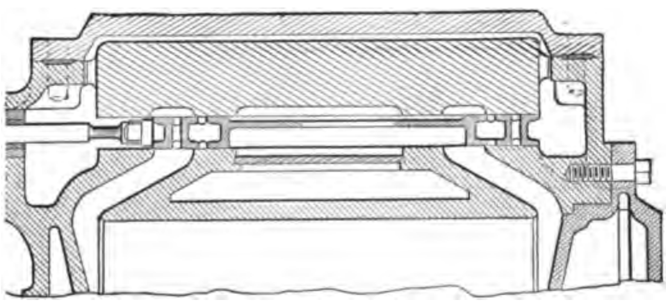


Fig. 53. Valve of Straight-Line Engine.

by a dashpot to prevent too sudden motion. Another feature is the relief-valve, at each end of the cylinder, the object of which is to give way in case any water gets into the cylinder, and thus save the cylinder-head from being knocked out, or other serious injury to the engine. This type is made in 15 sizes, from 10 to 250, one of which, directly connected to a dynamo, is shown in Fig. .

The Westinghouse Engine is another type in which the working-parts are completely inclosed. The engines are made in three styles, — the "standard," which is the original form, the "junior," and the "compound." They are all similar in general construction, and consist of a pair of vertical cylinders bolted to the top flange of the crank-case, which latter serves the double purpose of a pedestal for the engine, and a receptacle for the oil,

into which the cranks dip at each stroke. The pistons are of the trunk form, being open at the bottom, and are made sufficiently long (about 1½ times their diameter), to serve as crossheads, since the connecting-rods are directly attached to them. In the "standard" type the valve-chest is in the form of a third cylinder, which is in a slightly oblique position, and is often mistaken for a working cylinder. In the "junior" and compound engines the valve-chest is at right angles to the cylinders across the top. A single piston-valve is used in all of these engines, the valve-seat being a removable bushing in which the ports are milled.

The governor is of the shaft type, and consists of two weights controlled by springs. In the "standard" engine this governor is located on the shaft between the two cranks, and actuates the valve directly; in the "junior" engine it is located on the outside of the engine in one of the two fly-wheels; and in the compound engine it is carried in a special governor wheel, which takes the form of an inclosed case filled with oil. The governor weights are so pivoted that they act by inertia, as well as by centrifugal force, the object being to make the engine regulate more quickly for changes in load. Assume, for example, that the engine is running at normal speed, and that the weight *A*, pivoted at *B*, is in a certain position, as represented in Fig. 54, where its centrifugal force is balanced by the tension of a spring not shown in the figure. If, now, the load is suddenly reduced, the fly-wheel will run ahead of the weight *A*, so to speak, thereby swinging it, in a very small fraction of a revolution, into the position indicated by dotted lines, the rotation being in a left-hand direction. If load is suddenly added, the converse action will take place. Extreme quickness of regulation is not so important in electric lighting as in electric-railway work, since changes of load are more gradual. But promptness in this respect is very desirable for incandescent lamps, as the least change of speed affects the light, even though it only lasts for one or two revolutions, while an ordinary centrifugal governor is adjusting itself.

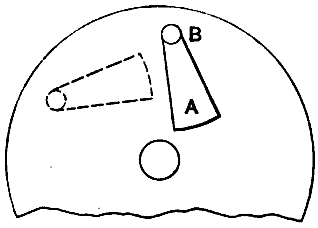


Fig. 54. Principle of Inertia Governor.

The "standard" engine is made in 13 sizes, ranging from 5 to 250 horse-power, the speeds being respectively 500 and 250 revolutions per minute. The "junior" engine is built in 7 sizes, from 5 to 75 horse-power, and speeds of 400 to 330 revolutions per minute. The Westinghouse Machine Company stated on Jan. 1, 1893, that they had sold 3,600 of the former and 1,700 of the latter type; nevertheless, these engines do not have the reputation of being particularly economical in steam consumption. They are

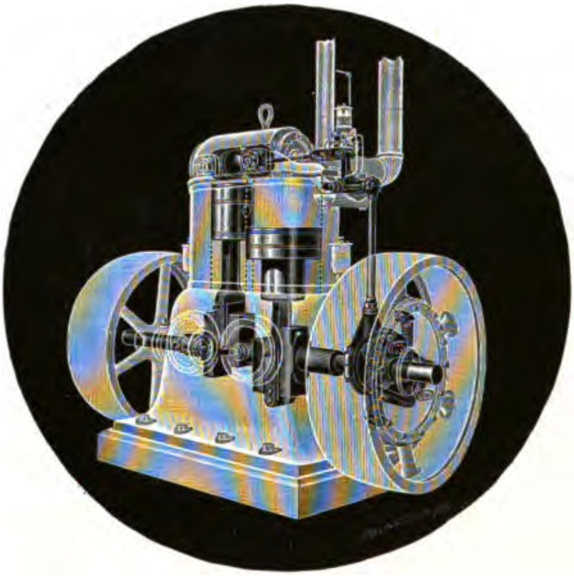


Fig. 55. Westinghouse Compound Engine.

employed where compactness, inclosed working-parts, and high speeds are desirable.

The compound Westinghouse engine is claimed to be of high economy, not only at full load, but also for variable loads. This engine is made in 11 sizes, from 35 to 700 horse-power, with speeds of 375 to 220 revolutions per minute (Fig. 55).

The Brotherhood Engine is a type used quite extensively in England and sometimes in the United States. It is somewhat similar to the Westinghouse engine in general character; but it has three working cylinders, and these are arranged radially with respect to the shaft, at 120° from each other. Each cylinder is single acting, and the engine runs at a very high speed.

Willans Engine. — Another type of high-speed engine which is already widely used in England where it originated, and is now being introduced into this country, is the Willans central-valve engine. This engine is very unusual in its construction; indeed, it might be said that many of its features are directly antagonistic to generally accepted ideas. The engine is single acting; that is to say, the steam pressure is exerted on only one side of the piston. The governor is of the simple throttle-valve form, the cut-off being set at a certain point and not controlled by the governor, whereas practically all American engines, whether high or low speed, are provided with an automatic cut-off when used in electric lighting. Another striking peculiarity of the engine is the location of the valve *inside of the piston-rod*, which is made hollow for the purpose. In spite of these apparent anomalies, the engine has been very successful, and seems to possess many advantages, the most prominent of which are, — great compactness and economy in floor-space; avoidance of lost motion and knocking, owing to the fact that the steam pressure is always exerted in one direction; automatic and perfect lubrication of bearings and other working-parts, obtained by inclosing them in a chamber partly filled with oil; and, finally, high speed, being from 350 to 500 revolutions per minute, which enables the engine to be directly coupled to the dynamo, securing a still further saving of space. The economy of this engine seems to be high, a steam consumption as low as 12.74 lbs. of steam per horse-power per hour having been obtained with a condensing-engine of this type of only 30 horse-power at 400 revolutions per minute, which is certainly a remarkable result. It is difficult to understand how very high economy can be secured with a throttle-valve governor, unless the engine is kept working at or near full load. An explanation of this apparent anomaly is given on page 133.

The engine is made simple, compound, and triple-expansion; but usually only the two latter kinds, with two sets of cylinders, are used in electric lighting.

The construction of the Willans engine is shown in Fig. 56, which represents a pair of compound engines connected to the same shaft. The two sets of pistons are each connected to their corresponding cranks by a pair of connecting-rods, with a space

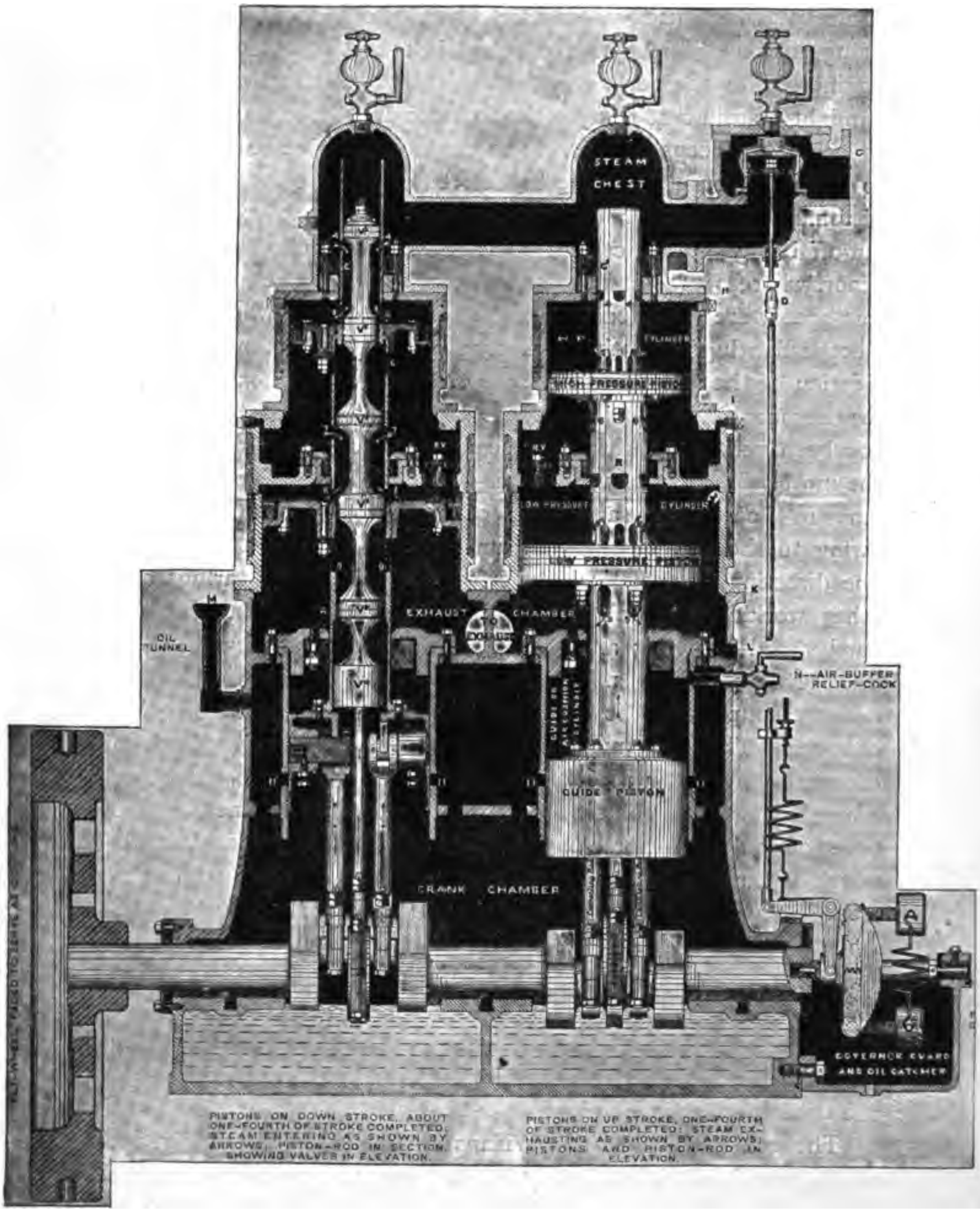


Fig. 56. Willans Central-Valve Compound Engine.

between, which contains an eccentric, forged directly upon the crank-pin. The connecting-rods work at the top upon two hardened steel pins, so supported that the pressure of the rods exerts no twisting strain upon them ; the eccentric-rod plays in the space between the former.

Piston-valves are used, moving *inside of a hollow piston-rod R*, which passes completely through the line of pistons, and through the ends of the cylinders. The reason that the eccentric is placed on the crank-pin, and not on the shaft as usual, is that the valve-face (i.e., the inside surface of the hollow piston-rod) *moves with the pistons.* Consequently the valve-motion required is a motion *relative to the pistons ;* and this is obtained by mounting the eccentric on the crank-pin, which, like the piston-rod, moves up and down with the pistons. Though its lead is set differently from that of an ordinary eccentric, its effect upon the movement of the valves is practically the same.

The steam passes from the steam-chest into the hollow piston-rod, which moves steam-tight through the gland in the cylinder top. It then passes out through ports 4 in the piston-rod, into the high-pressure cylinder; and on the return stroke it leaves the high-pressure cylinder by the ports 5, and enters the low-pressure cylinder by the ports 6. In each case its entrance and exit are controlled by the valves V^1, V^2, etc., working in the hollow piston-rod. The governor is of the simple throttle-valve type, the action of which is clearly shown in Fig. 56.

A test made by Siemens Brothers of London, under the superintendence of Professor Kennedy,* of a Siemens dynamo (type H. B. 27–40) directly coupled to a Willans compound engine (type III.), gave the following results:—

Load.	Pressure in Steam-Chest.	Revolutions per minute.	Amperes.	Volts.	I. H. P.	E. H. P.	Water, lbs., per E. H. P.	Efficiency, per cent.
Full	139	346	1001	225	343	302	23.8	88.04
Three-quarters	112	347	740	225	262.2	223.2	27.1	85.11
One-half	88	344	515	225	197.2	155.3	31.63	78.76
One-quarter	56	345	236	225	112.2	71.2	47.9	63.44

* *The London Electrician*, Feb. 2, 1894.

These results are remarkably good, the net efficiency at full load being 88 per cent, which allows for the losses in both the dynamo and engine.

An efficiency of 63.44 per cent at one-quarter load is also surprising, particularly when it is noted that the pressure in the

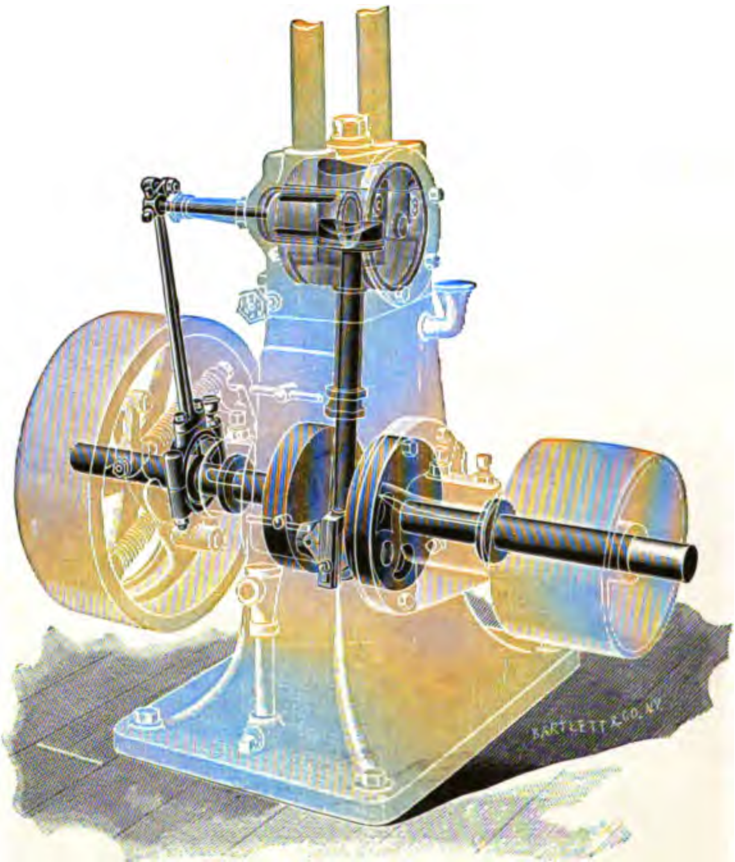


Fig. 57. Working-Parts of Case Engine.

steam-chest is then reduced from 139 lbs. to 56 lbs. by the throttle-valve governor. The Willans engines are especially intended for direct coupling with dynamos.

The Case Engine is an example of a very high-speed engine which is particularly adapted to being directly coupled to dynamos for small electric plants. Fig. 57 shows a skeleton view of the

internal arrangement and working-parts of this engine, which are inclosed in a cast-iron box. The cylinder is of the oscillating type, being capable of rocking in its casing, which permits the piston-rod to be directly connected to the crank-pin, and saves weight in the moving-ports by eliminating the connection-rod and cross-head. The cut-off valve is of the plug type, balanced and made with a slight taper, so that it can always be kept tight. Its only duty is to define the point of cut-off ; since the admission,

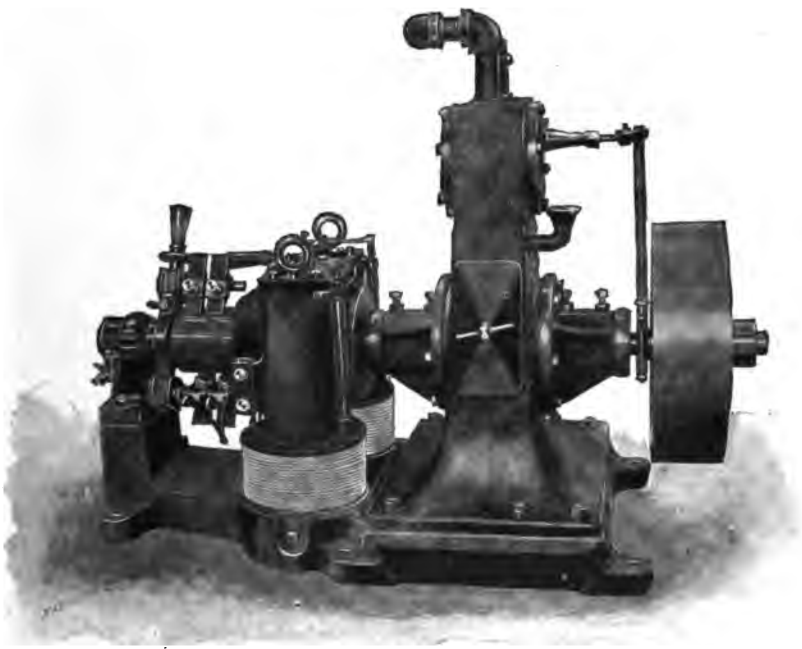


Fig. 58. Case Engine Combined with Crocker-Wheeler Dynamo.

release, and exhaust closure are controlled by the rocking of the main cylinder, which thus performs the valve-action. The governor is of the usual shaft type, except that it does not vary the throw of the valve, but effects the regulation by rotating the eccentric on the shaft, thereby changing the lead. The general experience with these engines proves that they regulate very well, and any slight change in speed can be offset by compound winding on the dynamo.

These engines are made in various sizes from 2.5 to 25 horse-

power, and are built in the pedestal form (Fig. 57), and also in the bracket and hanger types. The two latter may be mounted on the wall or ceiling where this may be desirable. A Case engine directly coupled to a small dynamo is shown in Fig. 58. This combination is adapted to small plants, and is also found to be very useful for running a few electric lights or motors in a store, factory, or theater, after regular hours, in order to enable the large engines to be stopped.

The 2.5 horse-power Case engine runs at 900 revolutions per minute, weighs 200 lbs., and occupies a floor-space of 11×15 inches. The 8 horse-power engine runs at 650 revolutions, weighs 600 lbs., the floor-space being 17×24 inches. The 25 horse-power runs at 550 revolutions, weighs 1,450 lbs., the floor-space being 28×29 inches. There are several intermediate sizes with corresponding data.

Medium-speed Engines. — Besides the types of high-speed engines just described, a third class of engines was defined (page

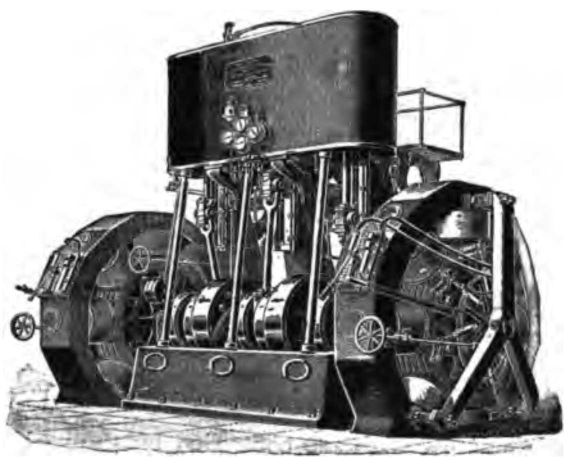


Fig. 59. Vertical Triple-expansion Direct-connected Engine.

156) to be those which are a compromise between the low-speed Corliss and the high-speed "Straight-Line" engine, for example. These are usually of the vertical marine type, but may be horizontal. They are compound, triple-, or even quadruple-expansion, and have a speed between 125 and 200 revolutions per minute. An example of this class is that shown in Fig. 59, being a vertical

triple-expansion engine directly coupled to a dynamo on each end of the shaft. This type is made in sizes up to 1,000 horse-power or more by the General Electric Company.

Other examples of this class are built by the Lake Erie Engineering Works. The cylinders of this engine are of the four-valve type, with separate ports for admission and exhaust. The valves are of the double-faced slide type, and are four-ported; the high-pressure steam-valve is wholly balanced, and the others, working under light pressures, are operated by independent gear. The lap is adjustable, permitting of advantageous setting for either condensing or non-condensing service. The governor and steam-valves are constructed to carry the steam as far as $\frac{3}{4}$ stroke in the first cylinder, should the demands of the load require it, thus permitting the engine to exert much more than its usual power.

The movement of the high-pressure admission-valve is controlled by a centrifugal shaft-governor, by means of which the engine is regulated as regards the speed of revolution.

The three cylinders of one size of this engine are 10, 16, and 25 inches in diameter respectively, with a stroke of 20 inches. The piston speed is 617 feet per minute, with 185 revolutions. The high and intermediate cylinders are jacketed with full boiler-pressure, the low-pressure cylinder being unjacketed. The bed-plate is heavy, and constructed for either direct or belt connection to generators.

This engine develops 300 indicated horse-power, with 160 lbs. initial pressure, cut-off at $\frac{1}{3}$ stroke, and will develop 500 indicated horse-power under the same conditions with 26 inches vacuum. It requires not more than 14 lbs. of dry steam per indicated horse-power, under the above-named conditions, nor more than $15\frac{1}{2}$ lbs. when working under loads varying from 200 to 450 horse-power. The variation in speed does not exceed $1\frac{1}{2}$ per cent between friction and rated loads. If one-half of the load is suddenly thrown off or on, the momentary variation of speed does not exceed $2\frac{1}{2}$ per cent, condensing or non-condensing. These engines are made in sizes from about 100 to 2,000 horse-power, and may be arranged with a fly-wheel for belt connection, as well as in the direct-connected form.

Several other similar types of engine are built by McIn-

tosh, Seymour, & Company, and other manufacturers. An interesting form of engine* is that designed by the Ball & Wood Company, in which the main valve-gear is of the Corliss type, but the automatic cut-off is obtained by independently operated valves placed inside the steam-valves, and controlled by a shaft-governor. This combination is intended to secure the great advantages of the Corliss valve-gear, and at the same time allow the engine to run at high speeds, which is not practicable with the ordinary arrangement.

Steam-Turbines. — The most radical form of engine now available for electric lighting is the steam-turbine, of which there are already several types in practical use. The advantages of steam-turbines are: —

First. Extreme compactness, a small engine, occupying no more space than an ordinary engine of 10 horse-power, being capable of developing 100 or more horse-power.

Second. The enormously high speed of the turbine makes it possible to directly couple it with a small dynamo, but the speed is so very high that it is sometimes found necessary to reduce it by gearing. In this respect it is exactly opposite to the ordinary engine, which is too low in speed. It would seem better, however, to construct an armature of small diameter, specially adapted to run at the high speed, in order to get the advantage of direct coupling.

Third. The steam-turbine would appear to possess possibilities of very high efficiency. This advantage is due to the fact that the wheel itself can be run with little or no packing or lubrication, a slight clearance being allowable without involving much leakage at the very high speed. The elimination of packing and lubrication would make it possible to use steam at a very high temperature and pressure, 300 lbs. for example. As a matter of fact, the pressure now used in steam-turbines is usually about 80 or 100 lbs.; but, even at that comparatively low pressure, these machines are fully as economical as the ordinary forms of steam-engine.

The velocity of the periphery of a steam-turbine must be very high in order to obtain good efficiency. This is because the velocity of steam issuing from a jet at any considerable pressure

* *Electrical World*, April 21, 1894.

is several hundred feet per second, and the circumferential speed of the turbine must be some large fraction of this (i.e. $\frac{1}{4}$ to $\frac{1}{2}$) in order to realize a satisfactory efficiency. The velocity of efflux of a jet of steam is often given * as $v = \sqrt{2gh}$, in which g is 32.2 the acceleration of gravity, and h is the height of a column of steam at the given density which would exert the same pressure per square inch. It is also stated † as a result of experiment that steam at any given pressure, flowing through an opening into any other pressure less than $\frac{3}{5}$ of the initial, has practically a constant velocity of about 890 feet per second.

The Parsons Steam-turbine avoids the necessity for extremely high speed by causing the steam to pass successively through a series of wheels. It is in use in the electric-lighting stations at Cambridge and Newcastle, in England, also on board vessels and in many other plants. A test by Professor Ewing shows a remarkably high economy of about 20 lbs. of water per horse-power hour for one of these turbines.

The De Laval Steam-turbine is another prominent type, consisting of a single wheel, as represented in Fig. 60, near the circumference of which there are passages having the curved form shown where a portion of the rim is removed for the purpose. Jets of steam are forced through these passages from inclined nozzles applied on one side of the disk, and flow out on the other side after giving up to the wheel a considerable portion of their energy. The principle of the action is similar to that of the water-turbine and Pelton wheel, explained in Chapter XIV. In actual practice the wheel is completely inclosed in a cast-iron case. The Laval differs from the Parsons device in the fact that it has only one wheel, and must, therefore, run at a higher speed in order to secure economy, as explained above, and actually

Fig. 60.

* Unwin's *Development and Transmission of Power*, p. 55; Thurston's *Manual of the Steam-Engine*, Part II., p. 159.

† *Steam*, Babcock and Wilcox, 1894, p. 89.

has a peripheral velocity of 574 feet per second. This corresponds to the enormous speed of 30,000 revolutions per minute, or 500 per second. In order to withstand the strain of such a speed, the wheel consists of a solid disk of steel, in which the steam passages are cut by a milling-machine. A steel ring is then shrunk on the outside. Even with the greatest care it is impossible to make the center of gravity correspond exactly with the axis of rotation. In the Laval turbine this difficulty is overcome by the use of a long flexible shaft, which allows the wheel to revolve about an axis passing precisely through its center of gravity, since by the principles of mechanics it tends to get into that position. The speed is reduced from 30,000 to 3,000 by means of a double set of spiral-gear wheels, 3,000 being the speed of the dynamo shaft. These turbines were exhibited at the Chicago Exposition of 1893, and one of them ran smoothly and with little noise at a speed of over 20,000 revolutions per minute, which is an extraordinary speed for gearing. The governor is attached to the shafts having the lower speed; and when it runs faster than the normal, weights are thrown out by centrifugal force acting against spring pressure, which throttle the supply of steam.

The results of "Tests of a 10 horse-power de Laval Steam Turbine," have been given by Professor W. F. M. Goss.*

* *Trans. Amer. Soc. Mech. Eng.*, December, 1895.

CHAPTER XII.

STEAM-ENGINES FOR ELECTRIC LIGHTING.

SELECTION, INSTALLATION, AND MANAGEMENT.

THE selection of the best size and type of steam-engine for a given electric lighting plant is, next to the choice of the system itself, the most important question which the engineer has to decide, since the satisfactory operation and working expenses of the station are directly dependent upon it.

The number of units in large central stations, whether steam-engines or dynamos, should be sufficient so that the disabling of one will not interfere with the proper running of the station; and, if possible, the number and size of units should be such that two of them may break down, and still allow the plant to carry its full load. The same idea may be expressed somewhat differently by stating that no unit should be more than one-quarter to one-tenth of the total capacity of the plant, and there should be one or two spare machines. In very small plants it is obviously impracticable to subdivide the power into many units, but, even in that case, it is always desirable to have at least two engines; and, if possible, each of them should be capable of carrying the ordinary load, or such a large fraction of it, that a sufficient number of lights can be run to give a reasonable supply, and not cause serious inconvenience in case of a stoppage of one engine.

In central stations of medium size the number of engines should be intermediate between those of a large station and a small plant, that is, from 3 to 6. There are exceptions to these general rules, some stations having one or two very large engines connected to a few large dynamos, or to a number of small ones. This plan has the advantage of simplicity and low first cost; but it has the disadvantages of practically shutting down the station if anything happens to one engine, and the economy of running a large engine during periods of light load would be very low. In fact, one or two auxiliary engines of smaller size would be a

very desirable addition to such a plant, not only as a safeguard in case of a breakdown of the main engine, but also for use when the load is small. This would make the total number of engines about three or four.

The relative size of the units, that is, the question whether they should be of the same or of different power, is often a perplexing point. The chief advantage of uniformity in size is the interchangeability of parts, and the possibility of having one or two spare parts which can be used in any engine that may happen to require them. On the other hand, the adoption of engines of different sizes may result in greater convenience and increased all-day efficiency of the plant; for example, in an isolated plant with which the author is familiar, there is one engine and dynamo of 750 lights capacity, and one of 250 lights, giving a total capacity of 1,000 lights. During the day and late at night the smaller engine can be run very economically with the load, which varies between 100 and 200 lights. When the load increases at the approach of darkness, the larger engine is substituted for the smaller, and supplies power for the 500 to 700 lights which are used during the evening. In this way each engine is almost perfectly suited to its load for long periods of time, the interval between the light load of the day and the heavy load of the evening being so short that the larger engine has to run for only a few minutes at an uneconomically light load; and for an unusually large load both engines can be run at the same time. In the design of central stations a similar judicious selection of engines may give excellent results. For instance, large compound or triple-expansion engines may be operated almost continually to carry the permanent portion of the load with high economy, but for the maximum load, which usually lasts only an hour or two, cheaper and simpler engines may be used.

A little ingenuity and judgment will suggest many other similar plans by which convenience and efficiency can be secured. Careful adaptation of the size, number, and type of the engines will largely overcome the serious drawback of low economy in electric-lighting plants, which arises from operating steam-engines with light loads and variable loads. In nearly every case it would be possible to so select the engines that at no time would any one or more of them be running below 60 or above 125 per cent of

its normal load. The latter limit is perfectly allowable (see page 190), and avoids the very low efficiency which results from running an engine at a small fraction of its full power. This arrangement might not be possible where the variations in load are very sudden, as they are in electric-railway work; but in electric lighting the changes are usually quite gradual, and almost always allow sufficient time to put on or take off engines.

This scheme would serve to accomplish practically the same result as the use of storage batteries in enabling the engines always to be run at high efficiency, and would avoid the complication of storage batteries and the loss of energy which occurs in charging and discharging them. In some cases the carrying out of this idea might be difficult, either because the load is continually varying throughout the entire twenty-four hours of the day, or because the number of lamps connected to the station might increase so that a proper proportion in the size of engines in the beginning might not be right a few months afterwards; and the conditions would also change greatly with the season of the year. This, however, could be foreseen more or less, and could be provided for in originally planning or increasing the capacity of the plant. This matter is treated further in connection with storage batteries in Chapter XXI.

In general, it may be stated that in central stations or large isolated plants it is desirable, or at least allowable, to have two sizes of engines. But more than this are objectionable. Many plants are in the unfortunate position of having installed several different sizes and types of engines at various periods of their history, corresponding to the conditions existing at each time. In many cases this cannot be helped; but often a little foresight will save a plant from becoming a museum, which represents by numerous examples the progress of steam and electrical engineering.

The type selected is largely determined by the size, small engines being usually simple, and large ones compound or triple-expansion. Similarly, small engines may be high speed, and large engines should be low or medium speed. If floor-space is valuable or limited, a vertical engine may be chosen. The question of the relative merits of direct coupling, belting, and other forms of connection between engine and dynamo, are fully discussed in Chapters XV. and XVI.

The proper size, number, and type of dynamos to select is considered in Chapter XIX.; but the question is not so important as in the case of engines, for the reason that dynamos can be run at half or even one-quarter of their full load without seriously impairing their efficiency. It is also a fact that a dynamo can be started and stopped much more quickly and easily than a steam-engine, and without the loss of energy involved in heating up the latter. Furthermore, a dynamo can be run free with only 5 per cent of its full power even when the field-magnet is excited, and with about 3 per cent if the field is not excited, whereas a steam-engine requires 8 to 12 per cent of its total power when running without load; hence there is much greater likelihood of mistake or loss in the selecting or handling of steam-engines.

The difficult problem of the relative advantages of simple, compound, triple-expansion, and also condensing engines, is one which the electric-light engineer is often called upon to solve. The highest authorities disagree widely on these questions, probably because so much depends upon the particular type and size of engine, and the conditions of use in each case.

Simple, compound, and triple-expansion engines have already been compared in a general way on page 152. In the actual selection and use of an engine, the simple or single-cylinder type has the great advantage of simplicity. This is particularly important in smaller sizes, and below about 50 horse-power it is doubtful if the saving in coal by a compound engine is worth the increased first cost and care which the additional complication involves. When, however, the size of an engine becomes considerable, it is a positive advantage to increase the number of parts in order to reduce the weight of each, so that they are more easily handled in building and repairing the engine. For vertical engines in particular it is evidently better in appearance and construction to have two or more cylinders arranged side by side than to have one large and clumsy cylinder.

The chief merit, however, claimed for compound engines is their higher economy; but it has already been pointed out (page 154) that a great deal of this gain is due to the higher steam pressure *per se*, and that the economy of a simple engine is also considerably raised by increased pressure. Thurston * states that a simple,

* "Economics of Automatic Engines," *Journal of the Franklin Institute*, 1893.

condensing, automatic cut-off engine of about 15 horse-power and 280 revolutions per minute showed the following results: —

Steam pressure above vacuum in lbs. . .	75	95	115	135	155
Back pressure above vacuum in lbs. . .	5	5	5	5	5
Most economical point of cut-off . . .	$\frac{7}{32}$	$\frac{3}{16}$	$\frac{11}{64}$	$\frac{5}{32}$	$\frac{9}{64}$
Lbs. of water per horse-power developed .	32.3	29	28.3	27.4	25.5

This table shows that increasing the pressure from 75 to 155 lbs., which is a little more than doubling it, reduces the steam consumed 21 per cent. As a matter of fact, the full theoretical gain due to this increased pressure is not very much greater than this; nevertheless, it is customary to employ compound engines with pressures above 100 lbs., and triple-expansion with pressures of about 150 lbs. or more. The chief objection to the use of simple engines with high pressures, and therefore high temperatures, is that the range of temperature is so great that it tends to cause very large losses by cylinder condensation. The apparently small loss from this cause in the results given above was largely due to high speed and complete compression, both of which reduce the change in temperature of the walls of the cylinder, and the cooling effect upon the incoming steam.

Another advantage of multiple-cylinder engines is the distribution of the strains; and in the case of incandescent lighting the flickering of the lamps due to the variation in speed at different points of stroke is practically avoided by having two cranks acting at 90° with respect to each other, or, better yet, by three cranks at 120°. Some types of compound engine, as, for example, the tandem-compound, have only a single crank, or the cranks act at the same angle, or at 180°, and the effect of the "dead center" is the same as in a single-cylinder engine.

Condensing-engines have already been discussed on page 147. In general it may be said that they are desirable, provided a suitable supply of condensing water is available and reliable, and provided the size of the plant (250 horse-power or more) warrants the expense and complication of condenser, pumps, connections, etc. The condenser has the effect of reducing the back pressure about 12 lbs. below that of the atmosphere, which corresponds to "a vacuum of 24 inches" of mercury. It is important, however, to note that the difference in *temperature* between steam at atmos-

pheric pressure (14.7 lbs. absolute) and at that of the condenser (3 lbs. absolute) would be 100° – 61° = 39° C. = 70.2° F.; whereas the difference in temperature of steam at 112 lbs. and 100 lbs. absolute pressure is only 168.9° – 164.3° = 4.6° C. = 8.3° F., which is less than one-eighth as much. For higher pressures the temperature difference is still less for a given difference in pressure. Hence the efficiency gained (see page 91) by reducing the pressure at the lower limit is far greater than by increasing it at the upper limit. This is clearly shown in indicator diagrams where, for example, the area included between the lines of 10 and 20 lbs. pressure is usually much greater than between 60 and 70 lbs., as represented in Fig. 61. The losses by conduction and radiation are also less in condensing engines with a given effective pressure, since the average temperature is nearer that of the atmosphere.

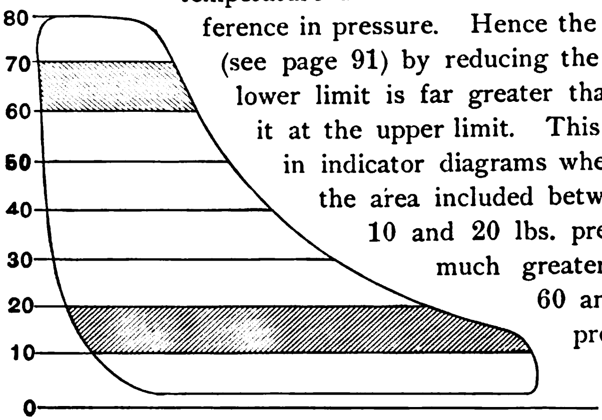


Fig. 61. Power Corresponding to Different Ranges of Pressure.

The best point of cut-off is almost always given as being between $\frac{1}{4}$ and $\frac{1}{5}$ of the stroke for a simple engine, and about $\frac{1}{3}$ for compound or triple-expansion engines. An earlier cut-off is considered objectionable because it increases the ranges of temperature, and therefore cylinder condensation; but the results given on page 187 show that a very early cut-off of $\frac{9}{64}$, or a little more than $\frac{1}{8}$, gives good economy with 155 lbs. absolute pressure. This, however, is partly due to the favorable conditions in that case. The most economical point of cut-off with only 95 lbs. pressure was found to be $\frac{3}{16}$, but it should always be remembered that the cut-off which gives the least steam consumption per horse-power should be raised somewhat in practice because the power of the engine increases with the cut-off (not proportionally, however) and a proper compromise between running expense and first cost should be made.

A steam-jacket around the cylinder is often recommended to reduce cylinder condensation, but it is seldom used in practice.

Superheated steam is also highly recommended for the same reason; but it is rarely employed, owing to the difficulty and danger of obtaining it. This subject was considered on page 153, and is discussed in works on the steam-engine.*

Cut-off and Throttle Governors. — The former type is used almost universally in this country for electric lighting, and is considered necessary to secure economy; but in England and on the continent of Europe, throttle-governors are often used.

This discrepancy has already been explained on page 133. In a recent paper by Charles Porter on "A Comparison of Fixed and Variable Cut-off," † he points out that governing by the latter method requires such an early cut-off at light loads that the waste from cylinder condensation is very large, owing to the fact that the ranges of temperature are great, and furthermore the loss due to filling the waste room at each stroke with steam at full-boiler pressure is much greater than filling it at a throttled pressure. The chief objections urged against throttle-governing itself, besides loss of steam-pressure, are slow or imperfect regulation. Mr. Porter claims to have overcome this by a "frictionless" governor and the elimination of the steam-chest. It would certainly seem that there is no inherent reason why a throttle-governor cannot be made as sensitive as an automatic cut-off governor. Thurston ‡ discusses the relative economy of the two methods under various conditions.

ECONOMY OF STEAM-ENGINES WITH VARIABLE LOADS.

One of the most serious difficulties in electric lighting is the fact that a plant is usually required to run for a large part of the time with a light load. The effect of this on the economy of an engine is very detrimental; the result being that the coal consumption in many electric-light stations, as well as small plants, is about twice as great as if the same total number of horse-power hours were developed by engines running uniformly at full load. Professor R. C. Carpenter has discussed this important matter quite fully in a paper on "The Variation in Economy of the Steam-engine due to Variation in Load." § He gives the pounds

* Thurston's *Manual of the Steam-Engine*, Part I., pp. 661–683.

† *Trans. Amer. Soc. Mech. Eng.*, vol. xvi., December, 1894

‡ *Manual of the Steam-Engine*, Part II., pp. 566–569.

§ *Trans. Amer. Inst. Elec. Eng.*, vol. x., May 17, 1893.

of water per horse-power hour required by the various types of engine with $\frac{1}{10}$, $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, 1, $1\frac{1}{4}$, and $1\frac{1}{2}$ times their rated capacity; and the general fact is that the water and also coal consumption per horse-power are about 50 per cent greater at $\frac{1}{2}$ load than at the rated load, and are over twice as great at $\frac{1}{4}$ load. This is shown very strikingly in a table and set of curves at the end of the paper. The variation in economy is not great between $\frac{3}{4}$ and $1\frac{1}{4}$ times the rated load; but beyond these limits, particularly below, the increase in water consumption is very rapid, and we should therefore carefully avoid operating an engine except within this range of power. It was pointed out in the beginning of this chapter that a judicious selection of the type, number, and size of engines will usually enable each engine, while in operation, to be run within the economical limits of load.

It is a well-known fact that the friction of most steam-engines is 8 to 12 per cent, and nearly constant for all loads. Professor Carpenter gives a number of tests of friction in various sizes and types. This is such a large factor in engines that it makes a great difference whether we consider indicated power or developed power. For example, at $\frac{1}{4}$ of the indicated load the actual power is only about $\frac{1}{8}$ of the full value, and the corresponding economy is extremely low.

The mistake of running steam-engines underloaded is very common, and is responsible for a large part of the inefficiency of electric light and power plants. The point of maximum efficiency is almost always made to correspond with the maximum load, whereas it should approximate the *average* load, since the full load may only exist for a few minutes each day. In other words, the engine should develop the average power at the best point of cut-off. As a matter of fact, the efficiency is not reduced as much by overload as by underload. Professor Carpenter shows that all types of engines consume only 5 or 10 per cent more steam when 50 per cent overloaded; but they require about 50 per cent more steam at half-load. Furthermore, an engine is not injured by overloading, the only effect being to decrease its speed, which may be counteracted by raising the steam-pressure, or by regulating the dynamo. This plan would also save nearly one-quarter in first cost, since the rated power of the engine would only be about three-quarters of its maximum output.

With a light load, the low-pressure cylinder of a non-condensing compound engine performs little or no work, because the governor (whether throttle or cut-off) allows only a small weight of steam to be admitted to the high-pressure cylinder. If, for example, the quantity of steam is such that it expands to atmospheric pressure in the first cylinder, then the piston of the second cylinder must do work against the back pressure of the atmosphere, and thus acts as a drag. Even with a heavier load, when the action of the second cylinder is not entirely negative, it would evidently be desirable to completely disconnect it in order to eliminate its friction and complication. In a condensing-engine, on the other hand, the back pressure, being almost wholly removed, the second cylinder always performs part of the useful work. Hence, for light or variable loads, it may not be desirable to employ compound engines except with condensers. This statement also applies to triple- or quadruple-expansion engines, and to a still greater extent.

Dr. Charles E. Emery, in a paper on the "Cost of Steam-power produced with Engines or Different Types under Practical Conditions," * gives very complete data. Professor Unwin's work on "The Development and Transmission of Power" also contains much information on this and allied subjects. This subject will be treated further in Volume II. as a part of Electric-lighting Management and Finance.

Foundations for Steam-Engines. — These have already been considered on page 59, and the means for avoiding the transmission of vibration from the engines were there explained.

The setting of the engine upon the foundation, and adjusting all of the parts in perfect alignment, should be carried out in the most careful manner. Almost all engines of 100 horse-power or less are provided with a cast-iron frame or base, upon which all the parts are mounted, and which makes the engine self-contained. This facilitates the setting of the engine, and avoids the possibility of the pillow-block or other parts getting out of line by the settling of a portion of the foundation. In very large engines, particularly if horizontal, it is not ordinarily practicable to mount them entirely upon one base; and one or both pillow-blocks or bearings are mounted on separate foundations, in which case it is

* *Trans. Amer. Inst. Elec. Eng.*, March, 1893.

of vital importance that the foundation itself, and the ground upon which it rests, should be perfectly solid, and free from danger of unequal settling.

The practical laying out and building of engine foundations is best carried out by making a complete template, or frame of wood, as already represented in Fig. 7. The builder of the engine should furnish a drawing by which this template may be made, so that it will hold the various bolts in exactly the proper positions while the brickwork is being built around them. This enables the foundation to be made ready to receive the engine as soon as it arrives, thereby avoiding considerable delay.

Lubrication of Engines. — Various kinds of oil are used to lubricate the bearings or other moving parts of machinery. These may be divided primarily into vegetable, animal, and mineral oils; but only the two latter are suitable for the purpose. The introduction of mineral oil is comparatively recent, sperm, lard, or some other form of animal oil having been used exclusively as lubricants, and even at the present time many engineers prefer them; but improvements in the manufacture of mineral oil, and its more extended use, have resulted in its being acknowledged to be as good as, or even better than, animal oil for machinery. Animal as well as vegetable oil is likely to be decomposed, with the formation of some organic acid. This change is what is commonly known as becoming rancid. The acid thus formed will corrode iron or other metal, which would be extremely objectionable in the case of a shaft or bearing. Mineral oil, on the contrary, does not form acid or any other deleterious substance, and for that reason is preferable to animal oil. It is usually much cheaper than animal oil of equivalent quality, and can be obtained of any desired viscosity.

The *quality* of oil is of the highest importance, and nothing is more foolish than to attempt excessive economy in this direction. The high cost of machinery, and the great importance of having it run as perfectly as possible, demand that only first-class oil should be used upon it. This is particularly true of cylinder oil which is used to lubricate the valves, interior of cylinder, piston, and piston-rods, which are the most delicate parts of an engine. Engines are ordinarily lubricated by means of a number of oil-cups placed where required. These usually have a sight-feed;

that is, the drops of oil which they supply can be seen and counted so that they can be adjusted by a screw or other device to the proper rate. Parts in motion are lubricated either by oil-cups placed upon them which are filled before starting, or by some form of "wiper" which scrapes off a certain amount of oil from a piece of felt or wicking at each stroke. The cylinder lubricator is an important attachment to an engine; and in some forms of engine the lubrication is effected not by oil-cups, but by inclosing the moving parts and causing them to run in oil, or splash it about so that it is carried to the various parts. Such forms are shown in Figs. 55 and 56.

A complete circulating-system of lubrication is sometimes employed, and is a very excellent and satisfactory method in plants of sufficient size to warrant it. All that is required is a small pump, which may be operated from one of the engines, or by a small electric motor. The pump forces the oil up to a tank, from which it flows, by gravity, through small pipes to the different parts of the several machines; thence it runs back into a receptacle, from which it is again pumped into the upper tank.

The filtering of oil after it has been used, to remove from it particles of metal or dirt which it may have accumulated, can be successfully carried on, and will effect great saving in the actual quantity of oil consumed. Many forms of filter suited to this purpose are manufactured.

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CHAPTER XIII.

GAS, OIL, AND HOT-AIR ENGINES.

GAS-ENGINES are not used as much in this country as in England or on the Continent, where they are almost as common as steam-engines. It is difficult to account for the difference in popularity of the gas-engine in Europe and America; but it is probably due to the fact that gas has not been very cheap in the United States until within a few years, and since that time electric motors have been introduced in such enormous numbers that gas-engines have not been required.

The advantages of the gas-engine over the steam-engine are:—

1. Cleanliness and freedom from drip, ashes, smoke, and other objectionable accompaniments of the steam-engine.
2. The boiler and the danger of boiler explosion are eliminated.
3. A licensed engineer, or even skilled labor, is not required to operate it.
4. There is much less loss of energy in starting and stopping a gas-engine than a steam-engine, and there is no waste during the periods when a gas-engine is idle between "runs."
5. The possibility of high efficiency, as set forth on page 78.

The disadvantages of gas-engines are:—

1. A large and expensive machine is required for comparatively small power; that is, an engine of given size will not develop more than about one-quarter as much power as a steam-engine of the same size. The gas-engine does not, however, require a boiler; hence the total bulk is less than that of the steam-engine, unless the gas-generating apparatus is included.

2. They are not self-starting, but require to be turned over by hand or by some auxiliary motor.
3. They are likely to stop when overloaded, and have to be started again by external power.
4. The ignition of the gas is somewhat troublesome, and there is liability of failure to explode.
5. The cylinder usually requires to be water-jacketed, in order to prevent its walls from becoming too highly heated.
6. Even with a water-jacket, the high temperature interferes with the lubrication.
7. They are rarely free from disagreeable odor.

Gas-engines as now used are of the explosive type; that is, a mixture of combustible gas and air is introduced into the cylinder, and there ignited by a small gas-jet, an electric spark, or an incandescent body. The high pressure resulting from the explosion acts upon the piston in the cylinder, and causes it to move and develop power. Most of the earlier gas-engines were very crude, on account of the loud noise which was produced by the explosion of the gas; and they were unsteady and spasmodic in their action, as the explosion occurred only once during several revolutions of the fly-wheel. Modern gas-engines of the best kinds are almost perfectly silent, and the explosion takes place at each stroke or in alternate strokes.

The typical action which takes place in most forms of gas-engine is as follows:—

A mixture of gas and air in the proper proportion is drawn into the cylinder by a stroke in one direction. On the return stroke the mixture is compressed. It is then ignited at the beginning of the next forward stroke, during which it exerts pressure upon the piston; and on the next back stroke the products of combustion are expelled from the cylinder: thus the cycle of operation comprises four separate actions; and four single strokes, or two complete revolutions, are required for each explosion or active stroke. Strictly speaking, therefore, the engine is half single-acting, and a very heavy fly-wheel is necessary to keep up the speed during the interval between the working-strokes. The compression of the mixture of gas and air previous to the explo-

sion might appear to be superfluous, since it would consume as much power as it would give back. *Previous compression* is, however, absolutely required to secure high efficiency: for if we take a mixture of gas and air at atmospheric pressure and explode it, its temperature and pressure would both be greatly increased; but, if allowed to expand down to atmospheric pressure, its temperature will still be far above that of the atmosphere, as represented at D, in Fig. 62, and it will contain a great deal of energy that cannot be gained from it except by expanding much below atmospheric pressure, which is obviously impracticable.

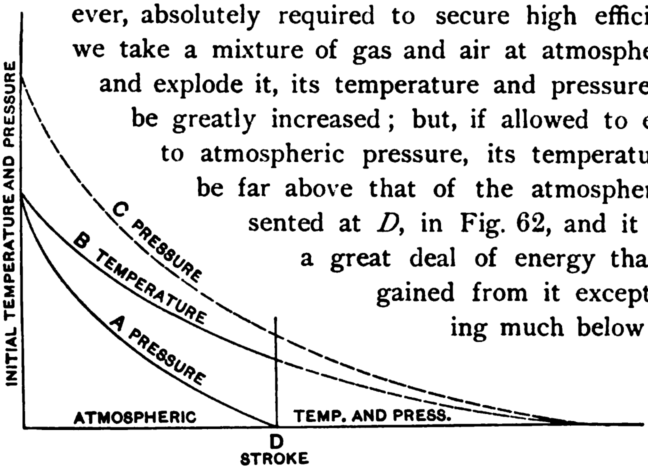

Fig. 62. Principle of Previous Compression in Gas-Engine.

If, however, the mixture is compressed prior to combustion, so that the pressure is raised, as represented by the dotted line C, it is possible to make the temperature, as well as the pressure of the gas, approximate that of the atmosphere at the end of the stroke, thereby getting out a much larger fraction of the energy contained in the gases.* This previous compression

* The exact effect of this compression may be calculated by means of the equations given on page 93. Assume that a certain volume of mixed gas and air at atmospheric pressure (15 lbs. per square inch) and temperature (20° C.) is exploded in the cylinder of a gas-engine, raising the products of combustion to 1500° C. Now, since $pv = RT$, and the volume v is kept constant, the pressure p will increase in proportion to the absolute temperature, T_1; that is, $p = 15 \frac{1500 + 273}{20 + 273} = 90$ lbs. per square inch. If, now, these heated gases expand adiabatically in the cylinder to atmospheric pressure, their temperature will become $T = T_1 \left(\frac{p}{p_1}\right)^{.29} = 1773 \left(\frac{15}{90}\right)^{.29} = 1060°$ absolute $= 787°$ C. Hence they still retain a large part of their thermal energy. If, however, they are compressed before explosion to one-sixth of their original volume, their pressure after explosion will be $6 \times 90 = 540$ lbs. per square inch; and expanded to 15 lbs., their temperature will be $T = 1773 \left(\frac{15}{540}\right)^{.29} = 627°$ absolute $= 354°$ C. Consequently the available energy remaining in the gases is very much less than before, the theoretical efficiencies in the two cases being respectively $\frac{1773 - 1060}{1773} = .40$ and $\frac{1773 - 627}{1773} = .65$. In practice, a great deal of heat would be lost through the walls of the cylinder, so that the actual efficiencies would be considerably lower.

is one of its most important points in the theory and practical working of gas-engines. It seriously complicates, however, the design and action of an engine, and requires either that one stroke of the piston be devoted to this compression, or that some outside pump or other device be added for the purpose. There would appear to be no way, however, to avoid the compression, and every gas-engine must accomplish it in order to operate efficiently. The fact that the gas must be compressed as well as drawn into the cylinder is the reason that gas-engines are not self-starting, one or two turns being required to put the engine into condition to act by itself.

Another serious difficulty in the practical working of gas-engines is the usual requirement of surrounding the cylinder with a *water-jacket*, through which cold water is caused to flow, in order to prevent the interior surface of the cylinder from becoming so highly heated that the lubrication or proper working of the piston would be rendered impossible. This requires either a constant supply of water or a large tank or pan in which the water is cooled, the circulation being produced by a pump. If, for any reason, the flow ceases even for a very few minutes lubrication is destroyed and the interior of the cylinder is likely to "cut" (i. e. become roughened). The water-jacketing absorbs a large amount of the heat of the gases, amounting in some cases to about fifty per cent of the total energy, which cuts down the efficiency enormously. In most forms of gas-engine it is also thought necessary to *explode the gas at or near the dead center*; that is, when the crank-pin is on a line with the piston-rod. This is done to take up the shock of the explosion, and prevent a sudden jump in the stroke. It tends to greatly diminish the power given out by the gases, since the maximum pressure existing at the instant of explosion is lost, the actual initial temperature at the beginning of the stroke being much less than that of combustion, and the efficiency of the engine is correspondingly reduced.

The ignition of the gas is another common source of trouble. The three means commonly employed are an incandescent tube, a small gas flame, or an electric spark. The first device consists of a tube of iron or refractory material, which connects with the cylinder, and is kept red hot by a Bunsen burner. The rather

rapid destruction of the tube is the chief objection to this plan. The second method requires that the interior of the cyclinder should communicate directly through a small passage with the flame which burns outside in the air. The electric spark is direct and neat, but involves a source of current and a coil; but in an electrical plant the former is always available. These devices sometimes fail to ignite the gas, in which case the latter is wasted, and the speed falls.

Gas Consumption. — The efficiency of gas-engines has been, and is now being, steadily increased. At present the consumption of ordinary illuminating-gas is about 20 cubic feet per horse-power hour in a fairly good engine of reasonable size. Even better economy than this is often attained; and figures as low as 17, or even 15, cubic feet per horse-power hour are often realized in actual practice. The efficiency of the gas-engine, like that of the steam-engine, is greatly reduced at light loads. Professor Unwin * gives the following table, —

Fuel Consumption in Gas and Oil Engines at Various Loads.

Brake load in per cent of full load.	Gas-Engine, cu. ft. of gas per brake H. P. hour.	Oil-Engine, lbs. of oil per brake H. P. hour.
100	21.65	1.00
75	23.78	1.13
50	28.05	1.40
25	40.85	2.20
12.5	66.45	3.80

Producer-Gas is now used in England, France, and other countries for gas-engines, and the results obtained are very promising; in fact, some of the lowest results in coal consumption ever recorded have been reached by its use. The process consists in converting the coal into gas by subjecting it to the action of air or a mixture of air and steam, preferably the latter. The producer consists of a brickwork chamber, into which the coal is fed through a hopper at the top, as indicated in Fig. 63. A sufficient quantity of coal is put in so that it forms a mass 3 to 5 feet in depth, depending upon the size and character of the coal. A mixture of steam and air is forced upward through the coal, the lower part of which is in a state of incandescence.

* *Development and Transmission of Power*, p. 55.

The resulting gas consists of a mixture of carbonic monoxide, hydrogen, and nitrogen, the theoretical reaction being $2\,C + H_2O + O + 2\,N_2 = 2\,CO + H_2 + 2\,N_2$. The exact reaction and the composition of the gas obtained depend upon the temperature, the proportion of steam and air used, and other conditions. In practice a small percentage of carbonic acid (CO_2) is produced, which involves a certain loss of fuel energy, and the introduction of a greater quantity of nitrogen. The nitrogen is a diluent which contributes nothing to the calorific power of the gas. Its presence is necessitated by the fact that a sufficient quantity of air must be introduced with the steam to keep the coal in a state of combustion. If steam alone were used, the temperature of the coal would fall rapidly, and the high temperature required would

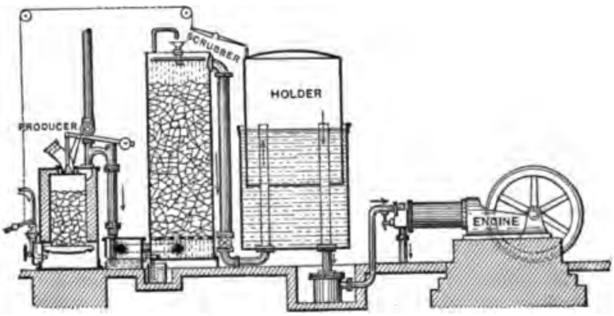

Fig. 63. Gas-Engine Operated by Producer-Gas.

have to be maintained by external heat, or by intermittently introducing air to raise the temperature and steam to produce the gas; in fact, these are the processes employed for the production of the ordinary water-gas for illuminating or heating purposes, which is also suitable for gas-engines. The advantage of the so-called producer process is that it is simple and continuous.

The pressure required is obtained by introducing the steam as a jet which draws in the air on the injector principle. The quantity of steam is regulated by a valve; and the supply of air can also be varied, so that the amount of gas produced, and also the temperature of the mass of coal, are perfectly under control. It might appear that most of the energy of the coal would be used up by converting it into gas in this way; but, as a matter of fact, the hydrogen and carbonic oxide produced by

the action of the steam and air on the coal are capable of developing nearly as much heat as the coal itself. Even the heat contained in the gases is given up to the coal as they rise through it, so that they leave the producer at a temperature of only a few hundred degrees, which avoids any considerable loss of energy. The gas is then passed through a "scrubber," to clean it, and finally into a holder, where it is stored ready for use in the engine, as represented.

Overcoming Unsteadiness of Gas-engine. — The gas-engine is often supplemented by a storage battery, the objects being to avoid the flickering in incandescent lamps, due to unsteady speed, and also to escape the waste of fuel at light loads, which the table (p. 199) shows. The addition of a storage battery allows the engine to be run at full load for any convenient period of the day, to charge the battery; the engine may then be stopped, and the lamps are fed during the remainder of the time by the storage battery. This plan is particularly applicable to a small plant in a private residence; for example, where the apparatus may be operated by a gardener or other employee in connection with his ordinary work. The gas or oil engine has a great advantage over the steam-engine in this respect; since it is not allowable for the latter to be run except by a regular engineer, whereas the former can be managed by almost any one after a little experience. The use of accumulators in connection with gas-engines is treated in Chapter XXI.

A heavy fly-wheel placed on the shaft of the gas-engine tends to prevent variation in speed due to the intermittent action; but it is still more effectual if a fly-wheel is also applied to the shaft of the dynamo. A spring or other elastic connection is interposed between the shaft of the engine and the fly-wheel on the dynamo, to take up the variations in speed. This may be accomplished by having the pulley of the dynamo mounted loosely upon its shaft, and connected to it by spiral or helical springs. It is often found in practice, however, that the ordinary belt-connection is sufficient to prevent the variation from being transmitted even if the pulley is rigidly attached to the dynamo shaft, provided the latter carries a fly-wheel also. The fly-wheel may consist simply of a heavy flange cast on one side of the pulley. It is desirable in this case to have the belt,

which may be an ordinary leather one, a little longer and slightly more slack than usual, in order that its elasticity and variation in sag may be sufficient to take up the impulses. As the gas-engine is more perfected, the necessity for special elastic connections becomes less. To eliminate the unsteadiness in the engine itself is far better than to correct it by extra devices. In fact, gas-engines are now being directly coupled with dynamos.

The Otto Gas-engine was brought out by Dr. N. A. Otto in 1867, since which time over 40,000 motors of this type have been sold. The original form was the Otto-Langen engine, which had a so-called "free piston" that was impelled upward by the explo-

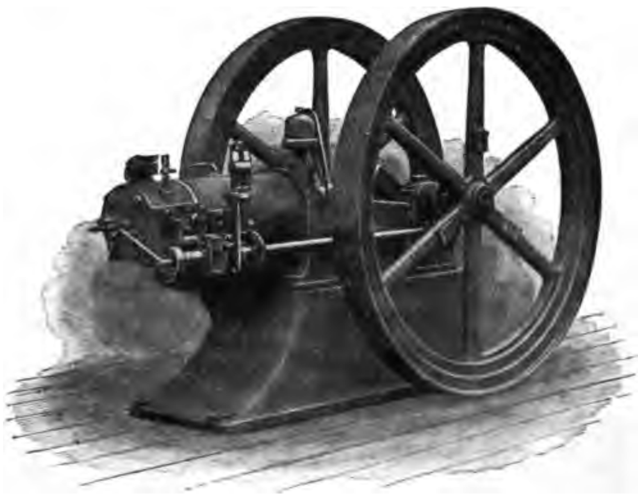

Fig. 64. "Columbian" Otto Gas-Engine.

sion of the gas below it. The piston then descended by its own weight and by the pressure of the atmosphere, there being a partial vacuum under it of 22 inches of mercury at the beginning of the down-stroke, due to the collapse of the products of combustion. The piston-rod had a rack formed upon it, which geared into a pinion on the fly-wheel shaft. This pinion turned loose upon the shaft during the ascent; but during the descent it engaged with and drove the shaft by means of a friction clutch, producing two revolutions during the down-stroke.

This engine was very noisy, the piston being thrown up with considerable violence by the explosions; and it was superseded by

the "Otto silent gas-engine." This type is manufactured by the Gasmotoren-Fabrik Deutz, at Deutz near Cologne, where it originated. A circular issued by this company in 1893 gives a detailed list of 1,070 of these motors, aggregating 12,700 horse-power, used for electric lighting alone. They are made in sizes from ½ to 100 horse-power, the larger ones being usually horizontal with twin cylinders; and the smaller sizes, which are made down to ½ horse-power, being either horizontal or vertical, and having either one or two cylinders. These engines are also designed for the use of benzine or petroleum.

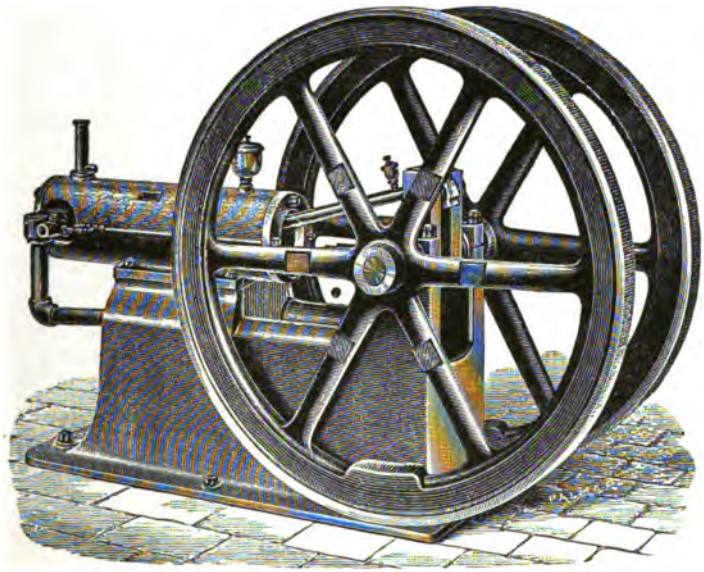

Fig. 65. White and Middleton Gas-Engine.

The Otto type of engine is also manufactured in England by Crossley Brothers of Manchester. The sizes and forms are, in general, similar to those made at Deutz. These engines are strongly built, finely finished, and run very smoothly. Many thousand of them are in use for electric lighting and other purposes.

The Otto engine is manufactured in this country at Philadelphia. Two types are made, — the "Standard," in which a slide-valve is used, and the "Columbian," having poppet-valves, which, together with the seats, can readily be taken out of the engine

for inspection or cleaning. Customers are given the choice of the electric-spark or heated-tube methods of ignition with the latter type of engine. These engines are made in sizes from 1 to 120 horse-power.

The White and Middleton Gas-engine is another successful form employed in this country for electric lighting and other uses. Fig. 65 shows the general design of sizes from 4 to 12 horse-power. A similar form is built in sizes from 15 to 60 horse-power. This type of engine has a single cylinder.

An advantageous feature of this engine is the fact that the waste gases are allowed to pass out through a port in the side of the cylinder, which is uncovered by the piston at the end of its stroke. In this way only the gases remaining in the cylinder (about one-tenth of the total quantity) are compelled to pass out through the valves, which largely frees the latter from the heat and dirt in the products of combustion.

The Fairbanks-Charter and the **Nash Gas-engines** are also well-known types.

Gasoline-engines. — Almost any gas-engine, with slight modifications, can be operated by gasoline. Some form of "vaporizer" is employed to convert the gasoline into vapor, which is then used in practically the same manner as ordinary gas. In the Otto gasoline-engine the liquid flows by gravity from a supply-tank outside of the building, through a galvanized iron pipe with soldered joints, directly into the cylinder of the engine, where it is vaporized by a current of air, the mixture being ignited by an electric spark or hot tube. A valve which admits the gasoline to the cylinder is controlled by a centrifugal governor, so that the quantity taken is only just sufficient to maintain the proper speed in spite of variations in the load. This type of engine is made in 14 sizes, ranging from 2 to 110 horse-power, the net weight of these two sizes being 875 and 24,000 lbs. respectively.

The greatest care should be taken to prevent the gasoline from leaking out of the pipes, valves, etc., as it is very inflammable. The gasoline commonly used in engines is that known as 74° or 76°; and the consumption is about one pint per horse-power per hour, or even less in the case of large and efficient engines. The ordinary cost of gasoline is 5 or 6 cents per gallon, which makes the cost of fuel only about $\frac{3}{4}$ cent per horse-power hour.

This is certainly a very reasonable figure for small units of power.

Petroleum-engines. — In these engines refined petroleum or ordinary kerosene is used; and since the oil is about 150° fire-test (i.e., it does not catch fire until heated to 150° F.), these engines are safe, whereas highly inflammable gasoline or benzine may be objectionable in certain places. These engines are well adapted to operating small electric-light plants, particularly where a supply of gas is not available, and where the location makes a gasoline-engine dangerous or undesirable. The consumption

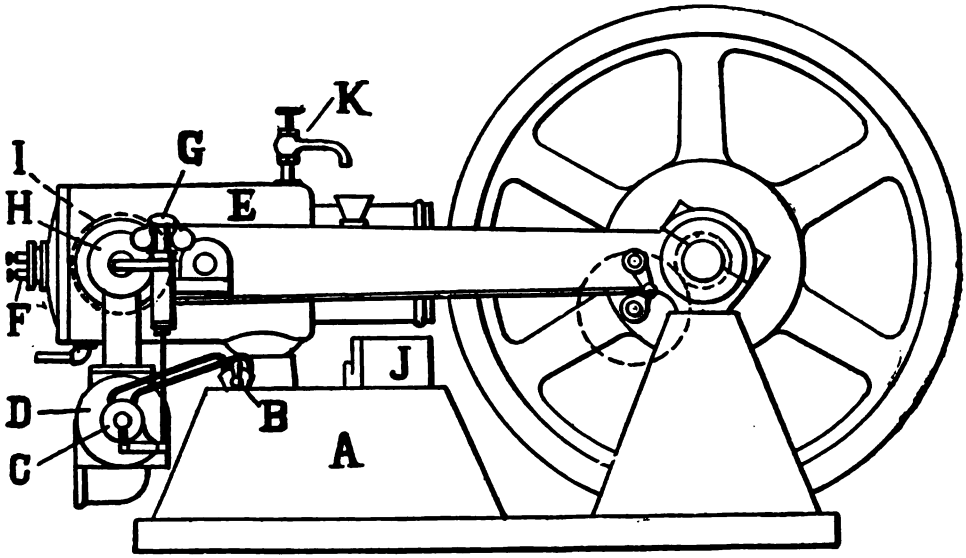

Fig. 66. Details of Priestman Engine.

of oil is nearly the same, being about one pint per horse-power hour.

The Priestman Oil-engine is a standard type used in England and in the United States.

In Fig. 66, which represents the arrangement of the American design of this engine, *A* is an oil-tank cast on the base, from which the oil, under pressure produced by an air-pump *J*, is forced through a pipe to the three-way cock *B*, and thence to the atomizer *C*, where it is met by a current of air, and broken up into fine particles, and sprayed into the mixer *D*, where it mixes with a

further quantity of air in the proper proportion, and is also heated by the exhaust from the cylinder passing around the chamber. The mixture is then drawn by the forward stroke of the piston through the inlet-valve, which is opened by the suction into the cylinder *E*, where it is compressed by the backward stroke of the piston, and ignited when the crank is on the dead center by an electric spark between the points of the ignition plug *F*. The governor controls the supply of oil and air, so that only enough is admitted to maintain the proper speed. The explosion, as in most gas or oil engines, takes place once in every two revolutions of the fly-wheel. The burned products are discharged through

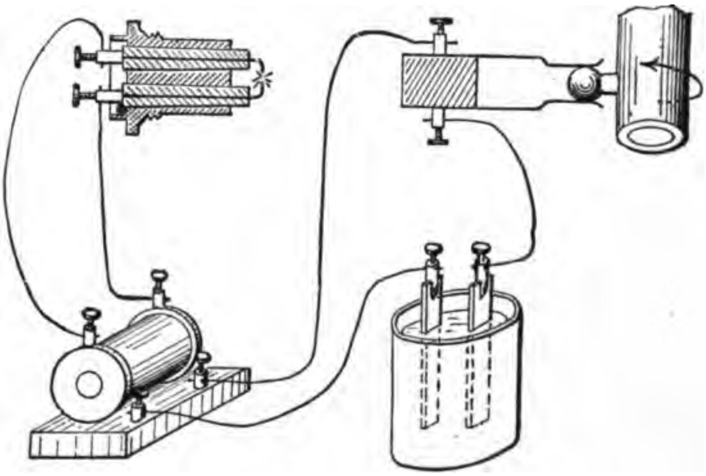

Fig. 67. Ignition Device of Priestman Engine.

the exhaust-valve *H*, which is held on its seat by a spring, and is opened by a cam and lever. *K* is the outlet of the water-jacket, which is required to keep the cylinder and exhaust-valve sufficiently cool. The inlet and exhaust valves are cast-iron poppet-valves with cast-iron seats and steel stems. The frame, main bearings, crank, and fly-wheel are very similar to those of the well-known "Straight-Line" steam-engines (page 167).

The ignition device, which is shown in Fig. 67, consists of an induction coil energized by a primary or storage cell or by the current from the dynamo. The primary circuit is closed and opened by a brass ball passing between the prongs of a fork also

of brass. The secondary wires lead through a brass plug which is fitted into the end of the cylinder, the wires being insulated by porcelain tubes, and their terminals provided with platinum points, between which the sparks are formed.

The Priestman oil-engine is made in the following standard sizes: 3, 7, 10, 14, 17, and 20 horse-power (actual); and larger sizes up to 120 horse-power are in process of construction.

The Saurer Petroleum-engine is another type which, in its general construction and action, is somewhat similar to the Priestman engine. It is built by The Thomson Electric Welding Company for use in connection with its work, and it has been applied with good results in small electric-lighting plants. Economy in oil consumption, and closeness of regulation, are among the merits claimed for these engines. The latter is essential in incandescent electric lighting, and these engines are said to be equal to the best steam-engines in this respect.

HOT-AIR ENGINES.

These machines are even more bulky than gas-engines compared with the power which they develop; but they might be employed for very small isolated plants, since they are so very safe and easy to manage. There are two classes of hot-air engines, — first, those in which air is heated and cooled alternately by contact with hot and cold surfaces; and second, those in which air is heated by mixing it with hot products of combustion.

One of the most successful types of the first class is the Rider hot-air engine. In this engine, which is called the compression engine, two single-acting cylinders are placed vertically a little distance apart, and connected at their upper ends by a regenerator composed of thin plates. One of these is the working or hot cylinder, under which a fire is maintained; the other is the air-pump or cold cylinder, surrounded by water to cool the air that is drawn into it, which air is pumped back into the hot cylinder. The plungers of these cylinders are worked by cranks placed at an angle of 95° on a shaft above. The working-plunger of a one horse-power engine has a diameter of $6\frac{3}{4}$ inches, with a stroke of $9\frac{1}{2}$ inches. The pump-plunger is $6\frac{3}{4}$ inches in diameter, with a stroke of 8.6 inches. The compression-piston first compresses the cold air in the lower part of the

compression-cylinder into about $\frac{1}{3}$ of its normal volume, when, by the upward motion of the working-piston and the completion of the down-stroke of the compression-piston, the air is transferred from the compression-cylinder through the regenerator and into the heater without any appreciable change of volume. The result is a great increase in pressure, corresponding to the rise in temperature; and this pressure forces the power-piston up to the end of its stroke. Sufficient pressure still remains in the power-cylinder to react upon the compression-piston, and impel the latter upward until it reaches nearly the top of the stroke; when, by the cooling of the air, the pressure falls to about that of the atmosphere, the power-piston descends, and the compression again begins. In the meantime the heated air passes through the regenerator, and leaves the greater portion of its heat in the regenerator plates, to be taken up and utilized on the return of the air through the heater. From indicator diagrams taken at 120 turns per minute, it appears that the effective mean pressure in the working-cylinder is 16.8 lbs., and that in the pump is 7.15 lbs. per square inch. Reducing the pump pressure in proportion to its stroke, it becomes 6.47 lbs.; hence $16.8 - 6.47 = 10.33$ lbs. per square inch is the net effective pressure on the working-plunger. The area of the latter is 35.78 square inches, and the net indicated horse-power is 1.08.

A hot-air engine of the second class was constructed by Belou in France.* This engine is of very large size, the compression-cylinder being 1 meter in diameter and 1.5 meters stroke, from which the air passes into a closed furnace, where it is heated by combustion taking place within it. It then passes to the working-cylinder, 1.4 meters in diameter and 1.5 meters stroke, where it acts expansively, after which it exhausts into the atmosphere. These cylinders are double-acting, and the feeding-cylinder draws 1 cubic meter of air with each stroke. The net useful work of this engine is 27.15 horse-power, with a coal consumption of 88 lbs. per hour, being 3.24 lbs. per net horse-power. This is a very large power for a hot-air engine, but the size of the engine is far greater than that of a combined steam-engine and boiler of equal power.

* *A Manual of Rules, Tables, etc.* By D. K. Clark, 1891 edition, p. 918.

The following are among the most useful works on gas and oil engines : —

The Gas Engine, by Dugald Clark, Third Edition, London, 1890.

Theory of the Gas Engine, by Dugald Clark, Second Edition, N.Y., 1891.

Gas, Oil, and Air Engines, by Bryan Donkin, London, 1894.

Les Moteurs à Gaz, by Gustave Richard, Paris, 1885.

Moteurs à Gaz et Pètrole, by Gustave Richard, 3 vols., Paris, 1892.

Gas and Petroleum Engines, by Professor Wm. Robinson, London, 1890.

Traité Théorique et Pratique des Moteurs à Gaz, by A. Witz, Third Edition, Paris, 1891.

The following descriptions of electric-lighting plants employing gas-engines are interesting : —

"The Belfast (Ireland) Gas Engine and Storage Battery Station," *Electrical Engineer* (N.Y.), Aug. 14, 1895.

"The Morecambe (England) Gas Engine Electric Light Station," *Electrical Engineer* (N.Y.), Oct. 30, 1895.

CHAPTER XIV.

WATER-WHEELS AND WINDMILLS.

WATER-WHEELS of various forms are, next to the steam-engine, the most important prime movers for driving dynamos. The advantage of water-power is its cheapness; but it has the disadvantages of being rather difficult to regulate perfectly and maintain a constant speed with a variable load, and it is usually very unreliable, being scanty, or failing entirely, during the summer, and being liable to great trouble from ice and floods during the winter and spring. The enormous water-power at Niagara, which is practically constant throughout the year, is absolutely without a parallel; and in practically all other places considerable trouble is caused by excess or deficiency of supply at different seasons. For these reasons the cheapness of water-power is sometimes more apparent than real, and from the inevitable laws of demand and supply its cost becomes nearly equal to that of steam-power when everything is considered. For example, it is often necessary to have an auxiliary steam-plant in case of failure of water-supply or break-down of the plant; hence the interest, depreciation, etc., upon this steam-plant should be included in the total cost of the water-power. When, however, a reliable water-power can be obtained, it usually enables electric current to be generated more cheaply than by steam-power; and there are many places in this country and abroad where this is very successfully accomplished. In fact, the practice seems to be almost universal to utilize, wherever available, a water-power for generating electricity for lighting or power purposes, even if the current has to be transmitted several miles. The actual cost of water-power is given in the papers of Mr. Samuel Webber and Dr. C. E. Emery, cited at the end of this chapter.

The principal types of water-wheels are, — overshot, breast, and undershot wheels, turbines and wheels of the Pelton type.

Overshot, and also breast, wheels receive the water at or near

their top, and it acts almost entirely by its weight to drive the wheel as it descends. The usual peripheral speed of overshot and high-breast wheels is from 3 to 6 feet per second, and their efficiency when well designed and constructed is from 70 to 80 per cent.

Undershot-wheels are driven by the impulse of water discharged against floats or boards from an opening at the bottom of a reservoir with a velocity corresponding to the head. The form of this wheel is similar to that of an ordinary paddle-wheel. Theoretically the best peripheral speed for such a wheel is one-half the velocity of the water; and they are usually run at about that rate, the actual efficiency being only about 30 per cent. This class of wheels was much improved by Poncelet, who curved the floats, and obtained a certain amount of reaction due to the dropping of the water, and thereby increased the efficiency to about 60 per cent. As a matter of fact, very few wheels of these three types are used in electric plants, much better results being obtained by turbines and tangential wheels.

Turbines are very extensively used for driving dynamos, and possess the great advantages of high efficiency, — being 80 to 85 per cent, — economy in space occupied, and close agreement in speed with that of the dynamo, so that the two can be directly coupled or easily connected by belting or gearing. The turbine is arranged to revolve either upon a vertical or horizontal axis; and there are also three types depending upon the direction in which the water flows through the wheel. These are, —*parallel-flow* turbines, in which the direction of the water passing through the wheel is approximately parallel to the axis; *outward-flow* turbines, in which the water is supplied at the center, and is discharged in currents radiating from the axis; and *inward-flow* turbines, in which the water enters at the periphery, and is discharged from the center. Turbines differ from other forms of water-wheel in the fact that all the vanes or blades are acted upon by the water at the same time, instead of only a portion of them, the action being equal and continuous on all sides. This tends to reduce the strains and friction, particularly in outward and inward flow turbines in which the pressure is almost entirely balanced in all directions. In the case of parallel-flow wheels, the upward thrust can be made to relieve the weight, or two tur-

bines may be combined so that the thrusts of the two counteract each other.

The principle of the turbine, and the reason for its high efficiency, is the fact that the water after passing through the wheel leaves it with a very small velocity; or, in other words, almost all of the energy is taken out of the water. To appreciate this, let us consider that *BB* in Fig. 68 represents a portion of the fixed guide-blades of a parallel-flow turbine into which the water enters from above, as represented by the arrow *A*, and strikes against the vanes of the wheel *CC*, causing it to revolve in the direction *EF*. The water is deflected by the curved blades of *CC*, until it flows out of the wheel in the direction *DE*. Now, if the forward velocity of the wheel is *EF*, and the backward velocity of the water with respect to the wheel is *DE*, then the water is delivered with an actual velocity *DF*, which is only about one-fifth of its original velocity when it entered the wheel; thus nearly all of the energy is taken from the water, and utilized to drive the turbine and machinery connected with it. If the wheel were designed to make the angle between the lines *DE* and *EF* smaller, the velocity *DF* would be still further diminished; but a certain angle and velocity are practically required for clearance, since the water must be delivered and flow away. All other forms of turbine operate on the same principle; in the outward-flow wheel, for example, the water is brought to the center with full velocity, and, after flowing outward in all directions, is delivered at the periphery with a velocity sufficient only to carry it out of the way of the water which follows it.

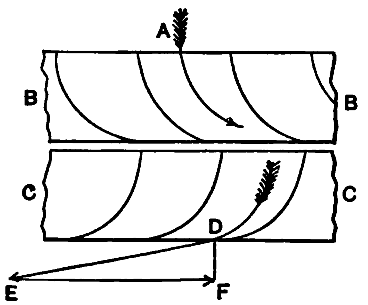

Fig. 68. Principle of the Turbine.

The energy in a moving mass is proportional to the square of its velocity, being $\frac{1}{2} mv^2$: therefore, if the water issues from the wheel with only $\frac{1}{5}$ of its initial velocity, it only retains $\frac{1}{25}$ of the initial energy; or, in other words, 96 per cent of the kinetic energy has been taken from it. There are, however, other losses in a water-wheel to be considered. These may all be put in the following form:—

$$\frac{WH}{33000} = P + p + \frac{Wh}{33000} + \frac{Wh_1}{33000} + \frac{Wv^2}{66000g}.$$

In this expression W is the weight in pounds of water flowing per minute; H is the total head or fall in feet: hence the first member is the total available horse-power. P is the actual brake horse-power developed by the wheel; p is the horse-power lost in friction of bearings; h is the head lost in resistance to the flow of water through the wheel and passages leading to or from it; h_1 is the head lost by the fact that the total fall cannot be utilized, since the wheel is usually placed a certain distance above the lower water-level, but a large portion of this energy is often saved by the use of a draught-tube; v is the velocity in feet per second at which the water issues from the wheel (represented by DF in Fig. 68); and g is the acceleration of gravity, which is 32.2: hence the last term gives the horse-power remaining in the water due to the velocity with which it leaves the wheel.

Development of a Water-Power. — The dams, raceways, wheel-pits, etc., which are required to make a natural water-power available for use are so extensive, and vary so greatly in different cases, that it is impossible to more than touch upon them in the present work. For information on this subject, reference may be made to the standard works on mechanical and civil engineering, and to the pamphlets of the various manufacturers of water-wheels.

Measuring the quantity of water which flows in a given time is the first step to be taken. This may be done in the case of small streams by constructing a temporary dam or weir over which the water flows through a rectangular notch, the quantity of water being calculated from "weir tables." In large streams the cross-section may be determined by carefully measuring the depth at a number of points on a line at right angles to the stream. This area multiplied by the mean velocity of the stream will give the volume of flow. The mean velocity is usually about 80 to 83 per cent of the maximum velocity in the middle of the stream, which latter may be found by timing a floating stick. The so-called *miner's inch* for measuring water-power is not the same in different regions, and is not a very satisfactory gauge. It is the amount of water that will flow through each square inch of an orifice which is a certain distance below the surface. This depth is usually 6 inches, in which case about 1.5 cubic feet of

water per minute will pass through each square inch of opening, the rate being slightly less for small openings of a few square inches, and slightly more for large openings. Measurements of the quantity of water should be made in the dryest season of the year, when the flow is the least; since the *minimum* amount of power usually fixes the practical value of a water-power. But in electric lighting it fortunately happens that in July and August, during which months the flow is ordinarily the least, the number of lamps is usually a minimum also; hence the full capacity of the plant may be more than the minimum water-power.

Water-power dams are made in innumerable forms, and of various materials, such as plank, timbers, logs, piles, stone masonry, etc. In most instances they involve a large part of the expense of a water-power plant, and almost every case is a special one, differing more or less from all others. In short, the design and construction of water-power dams constitute an important branch of engineering.

A canal, or raceway, is usually constructed to convey the water from the stream above the dam, or fall, to the point where the wheel is located. This should be of sufficient depth so that the water in it shall not flow more than 90 feet a minute. The mouth of the canal, or head-race, should be parallel with the direction of the stream, in order that ice, logs, and *débris* shall not be carried into it; in fact, it is still better if the opening of the canal, or raceway, faces down the stream at an angle of 10° or 20°, which still further reduces the chance of ice or driftwood floating into it. The canal, or race, should also be protected by a floating boom of timber extending across the entrance.

A flume, or forebay, built of planking or masonry, leads from the canal, or head-race, and conveys the water to the penstock. A rack or screen made of iron bars and rods should be placed in the flume, or forebay, and inclined backward at an angle of 45°, to cause the *débris* to be brought to the surface and easily removed.

Wheel-Pit. — It may happen that the formation of the ground makes it possible to arrange the turbines on the bank of the stream, and simply inclose them in a building or casing. Usually, however, it is necessary to dig a pit, in which the turbines are located.

A Penstock made of sheet iron or wood planking conveys the water from the flume, or forebay, to the wheel. In the penstock, which is usually vertical, the actual descent of the water takes place; but, if more convenient, the penstock may be inclined, the effect being due simply to the vertical fall. The turbine is located in, or connected to, the bottom of the penstock. Penstocks made of $\frac{3}{8}$ or $\frac{1}{2}$ inch sheet iron or steel riveted together are usually employed in the best practice, as they have the advantages over planking of compactness and less liability to leakage. A flange on the end of the penstock may be bolted directly to a corresponding flange on the turbine. A gate should be provided at the entrance to each penstock to control the flow of water; and in cases where the penstock is divided into several branches to supply different wheels, there should be a gate in each branch. Racks or screens made of iron bars and rods are also needed at the entrance to the penstock.

Draught-Tube. — The turbine may be located at the foot of the total fall; in fact, it may actually be placed below the surface of the lower water-level, that is, submerged in the tail-water. It is usually preferable, however, to raise it somewhat, in order to make it more accessible, in which case a draught-tube is connected to the turbine. This may be of any reasonable length, provided its vertical height is not more than about 18 feet, and still realize the full effect of the total fall of water, since the draught-tube, which should be air-tight and submerged at its lower end, acts by suction. There should be a space below the bottom of the draught-tube at least equal to its own diameter, so that the water may be delivered freely, otherwise it backs up and interferes with the action of the wheel. In the case of a turbine with a horizontal shaft, the use of a draught-tube is practically essential; since the wheel must be raised some distance above the lower water-level, which also permits the dynamos to be conveniently belted or directly coupled to the turbine-shaft. The arrangement of the penstock and draught-tube is shown in Fig. 69.

A tail-race or tunnel must be constructed to carry away the water, unless the wheels deliver it directly into the stream below the dam or fall. In the case of the enormous plant at Niagara Falls, a tunnel about 20 feet in diameter and 7,000 feet long leads from the bottom of the wheel-pit, which is 175 feet deep, and is

located near the bank of the river, about a mile above the falls, and empties into the river below the falls. The cross-section of the tail-race or tunnel should be so large that the velocity of the water in it shall not exceed 90 feet per minute, as in the case of the head-race. In fact, this rule applies to all passages leading to or from the wheel, hence they should have a cross-section of one square foot for each 90 cubic feet of water used per minute by the wheel.

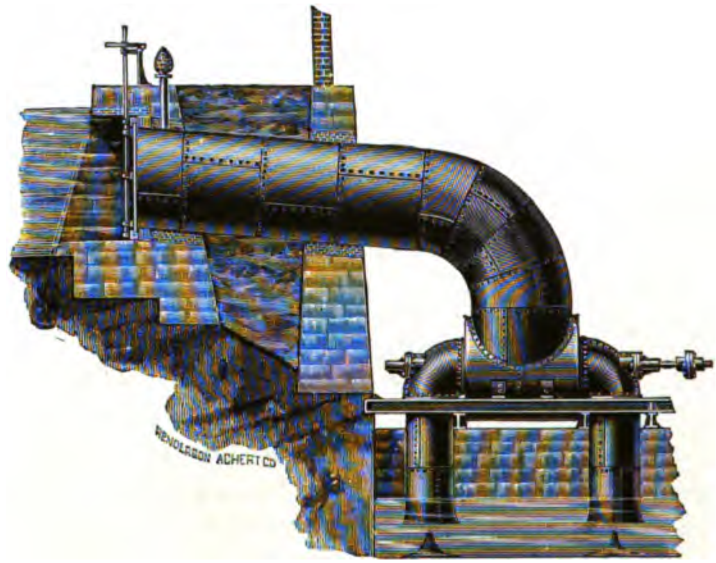

Fig. 69. Arrangement of Penstock, Turbine and Draught-Tubes.

Some of the most important forms of turbine in general use are the following:—

The Leffel Turbine, manufactured in Springfield, Ohio, is one of the standard types, and is made in many different forms suitable to various purposes. The ordinary vertical form, shown in Fig. 70, is usually inclosed in a globe casing, which secures strength and ample space for the circulation of water around the wheel. The water enters this casing through a pipe bolted to the inlet flange, which in the figure is shown facing the observer; it then runs from all sides into the turbine, which is of the inward-flow type, and finally discharges through a draught-tube, which is bolted to the flange shown at the bottom of the casing.

The casing of the Leffel wheel is provided with a cover bolted on the top, which can be removed at any time, allowing the wheel to be lifted bodily out of the casing. A large manhole, as well as handhole, on the side, admit of examination, or the removal of any obstruction that may get into the casing. A bridge-tree is firmly bolted to the top cap, and carries an oil-bearing supporting the upper end of the water-wheel shaft, to which latter a clutch-coupling is attached. Stuffing-boxes are arranged in the cap, through which the gate-rod and wheel-shaft pass, preventing any

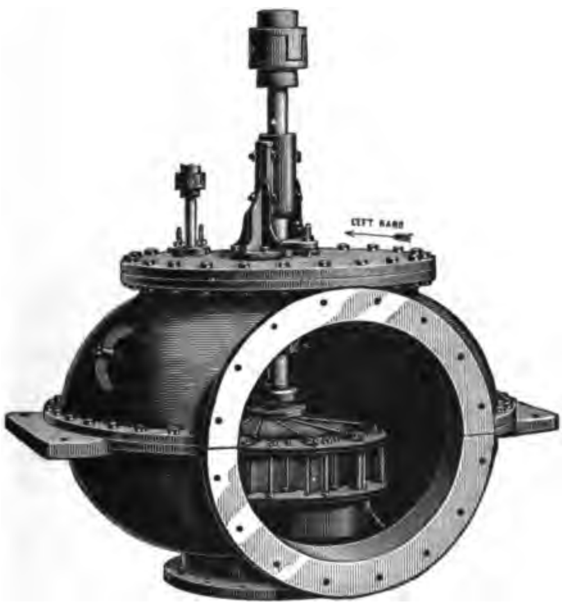

Fig. 70. Leffel Turbine.

leakage of water; and bolts are provided for tightening the packing, should it become loose or worn. A casing similar to the above, but of cylindrical form and made of heavy sheet iron riveted, is often employed for the larger sizes of Leffel wheels. It is not essential, however, to use the globe or cylinder casing, and in some cases the wheels are set directly in the bottom of a penstock built of planking. The horizontal types of Leffel wheels are quite similar in general construction, except that they are often made of the "double-discharge" type, analogous to the Victor turbine shown in Fig. 71. The flow of water and power of the Leffel

wheels is controlled by opening and closing the "gates" (i.e., blades), through which the water enters the wheel all around its periphery. These are caused to swing open more or less by the gate-rod, shown on the left of the main shaft in Fig. 70. This gate-rod is either operated by hand, or it may be controlled automatically by a centrifugal governor.

The Leffel wheels are made in various types, and of 22 standard sizes ranging from 10 to 87 inches in diameter and $5\frac{3}{4}$ to 615 horse-power, with 20 foot head of water.

The Victor wheel is another well-known type of turbine, manufactured by the Stilwell-Bierce and Smith-Vaile Company of Dayton, Ohio. It is made in many different forms and sizes, one standard form being that illustrated in Fig. 71, which is of

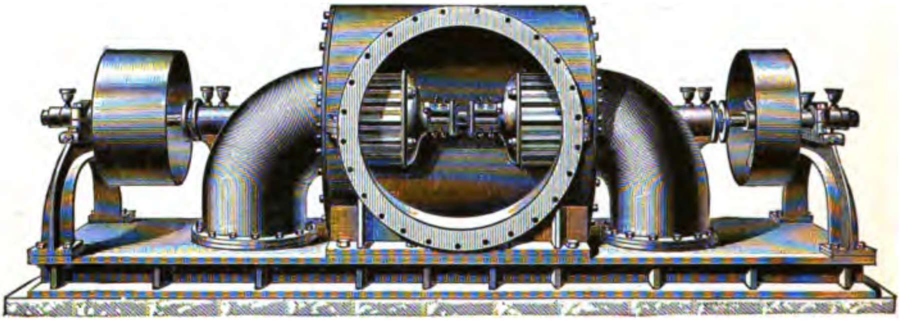

Fig. 71. Victor Double-discharge Turbine.

the double-discharge type, the water entering through a pipe bolted to the large flange shown on the front, and flowing out through both wheels into the discharge-pipes on either side.

Water-Wheel Governors. — Water-wheels are employed for many purposes in mills and factories where the load is fairly constant, and where small variations in speed are not very objectionable. In such cases regulation of the speed by opening and closing the gates by hand is sufficient; but for electric lighting an almost perfectly constant speed is required, and some form of automatic governor is usually necessary. Considerable difficulty has been experienced in the perfection of water-wheel governors, but several forms have recently been developed which give good results. Most of the manufacturers supply governors in connection with their turbines, if desired.

The Lombard water-wheel governor, made in Boston, Mass., is a special type, which is in successful operation, and which is claimed to maintain a constancy of speed comparing favorably with good steam-engine governors. This governor consists essentially of a hydraulic piston which operates, by means of a rack, pinion, and gears, the gate mechanism of the turbine, the motion of the piston being controlled by a centrifugal governor.

This form of governor, and results obtained with it, are fully described in the *Electrical Engineer* of April 3, 1895.

The mechanical connection of the turbine with the dynamo is

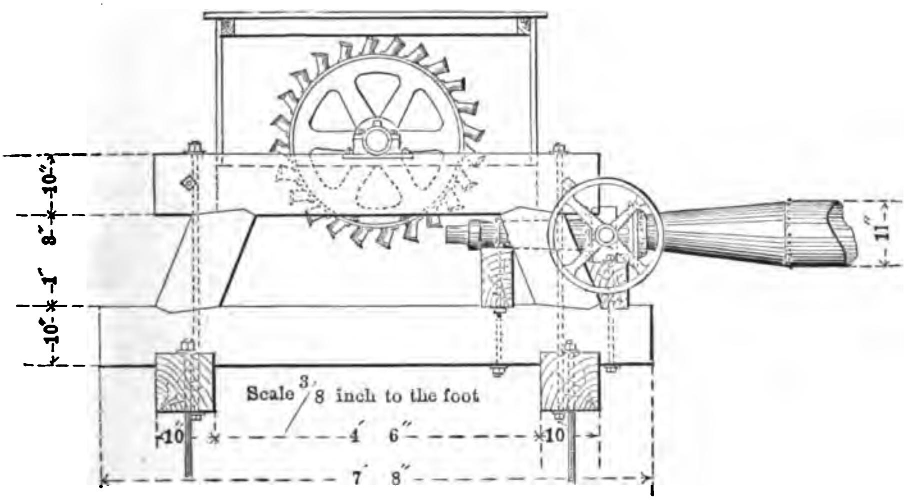

Fig. 72. Pelton Water-Wheel.

accomplished by direct-coupling, belting, or gearing, which subjects are treated in the two following chapters.

The Pelton Water-Wheel belongs to the class of tangential or impulse wheels, in which a jet of water issuing from a nozzle strikes against vanes or buckets projecting from the periphery of the wheel, as represented in Fig. 72. They are also called "partial turbines," because the water only acts upon a portion of the buckets at a time. These wheels are particularly adapted to very high heads of 100 feet or more; and one of them, installed at the Comstock mines in Nevada, runs under a vertical head of 2,100 feet, equivalent to 911 lbs. pressure per square inch.

The diameter of this wheel is 3 feet; and it runs at 1,150 revolutions per minute, developing 100 horse-power with a nozzle-tip only $\frac{1}{2}$ inch in diameter, the weight of the wheel being 180 lbs., or 1.8 lbs. per horse-power.

The great advantage of this type is its extreme simplicity and compactness; and at the same time it gives a high efficiency of 80 to 85 per cent, which is equal to that of the best turbines. The efficiency of the tangential wheel depends upon a principle similar to that of the turbine, as explained in connection with Fig. 68. The jet of water J strikes against a bucket B having the general form shown in Fig. 73, and is divided into two equal parts by the wedge in the middle of the bucket. Each of these streams S and S is deflected around by the concave surfaces on each side of the bucket, and is delivered backward at a velocity approximately equal to that of the wheel. The streams SS should flow out at an angle to the plane of the wheel in order to clear the next bucket C, as shown, otherwise a back pressure would be produced. This angle corresponds to DEF in Fig. 68. The action and efficiency of these wheels depend almost entirely upon the form of the buckets, which has been developed partly by theory, but chiefly by trial. The history and principles of tangential wheels are discussed quite fully in an article entitled "Tangential Water Wheels," by John Richards.*

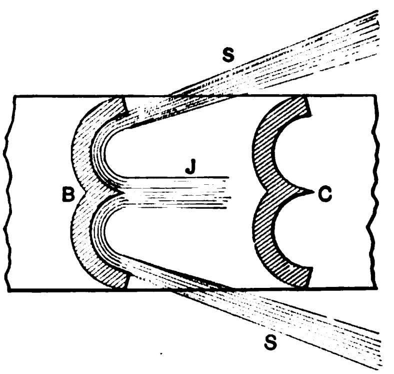

Fig. 73.

Regulation of Pelton Wheels. — The speed and power of these wheels can be controlled by varying the size of the jet, or by using several nozzles acting at different points on the periphery, which are turned on or off according to the power required. Either of these methods can be employed to reduce the power to about $\frac{1}{4}$ of the full amount, and still permit of good efficiency. The automatic maintenance of constant speed, which is so important in electric lighting, is secured by the Pelton differential gov-

* *Cassier's Magazine*, December, 1893.

ernor, which acts by deflecting the nozzle so that the jets do not strike the blades squarely.

Setting up and connecting.—A Pelton wheel is mounted upon a timber frame, as represented in Fig. 72, or an iron base bolted to suitable foundations. To prevent the water from scattering about, the wheel is inclosed in a housing of wood (Fig. 72) or iron, which should have ample clearance on all sides for free discharge. The nozzle should be firmly braced or anchored, particularly when working under a high head, since the jet produces a strong reaction. Several sizes of nozzle are provided, which can readily be unscrewed and changed to give different power. The water is usually brought to the wheel from the canal or flume by a pipe made of riveted sheet iron or steel, covered inside and out with asphalt to prevent corrosion. The pipe, which is usually made in lengths of 20 to 27 feet (the length of a freight-car), is united by slip joints in which the ends telescope together; or for large or high-pressure pipes lead joints should be used. These are made by surrounding the ends of the two pipes where they come together with a sleeve large enough to give a space about $\frac{3}{8}$ of an inch all around, into which lead is run. These pipes should be securely anchored with wire rope where the grade is steep, as is often the case.

The mechanical connection of a Pelton wheel to a dynamo is a very simple matter; since the shaft of the wheel is horizontal, and the speeds usually correspond closely. Hence a simple belt or rope connection between the pulleys of the wheel and of the dynamo may be used, or in many cases the two may advantageously be directly coupled together by one of the methods described in the following chapter.

The setting up and connecting of a Pelton-wheel plant for driving dynamos is described in detail, including the automatic governor already referred to, by George H. Winslow in a paper on "Long Distance Transmission at 10,000 Volts." *

The Girard Water-Wheel is another example of the tangential or jet type, which is quite extensively used in Europe, where it originated, and is now being manufactured in San Francisco. Like the Pelton wheel, it is especially adapted to high heads of water; in fact, it is similar to the former in principle and applica-

* *Trans. Amer. Inst. Elec. Eng.*, vol. xii., June, 1895.

tion, the chief difference being in the form of the buckets. This wheel is shown and described in the *Electrical Engineer* (N.Y.) of Sept. 18, 1895.

The Advantages of the Tangential Wheel may be summed up as follows: —

1. High efficiency.
2. Extreme simplicity and freedom from trouble.
3. Compactness.
4. Ability to vary power with good efficiency.
5. Adapted to any head from 50 to 2,000 feet.
6. Can be conveniently and effectively connected to dynamo.
7. Will run with water containing mud or grit which would clog or wear an ordinary turbine.

Water-Motors. — This name is usually given to any small hydraulic engine, even though it may be a turbine or Pelton wheel; but many forms are made with reciprocating pistons similar to steam-engines. Water-motors may be connected to the city water supply in places where the pressure and abundance are sufficient, but usually the water-tax would be prohibitive. In case a reliable and reasonably cheap supply is available, it affords a very convenient power for driving a small dynamo.

The Backus water-motor is a well-known type, which is made in 10 sizes, from 7 to 45 inches in diameter, developing $\frac{1}{8}$ to 15 horse-power, with water-pressures from 20 to 150 lbs. per square inch.

WINDMILLS FOR ELECTRIC LIGHTING.

Quite a number of electric-lighting plants are operated by the power obtained from windmills; but the obvious difficulty is the unsteadiness of the wind, which is particularly objectionable in incandescent lighting, because the slightest variation in voltage is perceptible in the lamps. This difficulty is more or less overcome by the use of a storage battery, which is charged by the windmill and dynamo, the actual current for lighting being obtained from the battery.

According to the observations of the United States Signal Service,* the average velocity of the wind for the year is 9 miles per hour along the North Atlantic coast and in the North-

* "Horse-power of Windmills," *Scientific American*, July 8, 1893.

western States; 10 miles on the plains of the West, and 6 miles in the Gulf States. A 10-mile breeze exerts a pressure of about $\frac{1}{2}$ lb. per square foot; 15 miles, $1\frac{1}{10}$ lbs.; 20 miles, 2 lbs.

The apparatus required for an electric-lighting plant consists of a windmill of any of the numerous types which are manufactured, and a dynamo having a capacity equivalent to the maximum power of the windmill, the two being mechanically connected by belting or gearing. It is also necessary to apply some automatic device which will cause the dynamo to charge the storage battery only when its speed and voltage rise above a certain value. This device may be either mechanical or electrical. For example, a centrifugal governor can be combined with a switch so as to close the latter when the speed reaches a certain limit, and open it when the speed falls below this value; or an electromagnetic device may be adopted which will close the circuit when the voltage of the dynamo rises to the proper point. If such a device were not used, the battery would discharge back through the dynamo when the voltage of the latter fell below the *E.M.F.* of the former.

Another device to maintain a reasonably constant voltage with wide variations in speed consists in winding the field-magnets of the dynamo differentially; that is, with a series-coil which opposes the magnetizing effect of the shunt-coil, so that, as the speed of the dynamo and the current which it generates increase, this series-coil will tend to demagnetize the field and keep down the *E.M.F.* of the dynamo. This would seem to be a simple and effective means of producing an approximately constant voltage with the very great changes in speed which would always occur in windmill plants.

It has been proposed to employ other methods for the storage of energy in place of the secondary battery; for example, the windmill may be arranged to pump water up to a tank, by which supply a water motor could be operated. In this way a constant head of water and speed of dynamo could be maintained; but the size and cost of a tank or reservoir sufficiently large to bridge over the long periods of calm weather would be so great as to make this plan impracticable in most cases. It has also been suggested that the windmill could be used to compress air in suitable reservoirs for operating air-engines; although in this case

the air-pressure would vary greatly as the reservoirs emptied, this variation being as great, perhaps, as that of the wind velocity itself. Mr. Rankin Kennedy discusses both of these mechanical methods of storage in the *London Electrical Review* of Dec. 21, 1894.

Descriptions of windmill electric-lighting plants in actual operation may be found in the *Scientific American* of Dec. 20, 1890, where the plant of Mr. Charles F. Brush of Cleveland, Ohio, is quite fully set forth. In this case the windmill is 56 feet in diameter, and drives a dynamo of 1200 watts capacity, which supplies current to 350 incandescent and 2 arc lamps, as well as 3 electric motors, about 100 of the incandescent lamps being in daily use. 408 storage cells, each having 100 ampere-hour capacity, are used in connection with this plant, being arranged in 12 series of 34 cells each.

Other descriptions of existing plants may be found in the *Electrical World* of June 10, 1893, and Feb. 3, 1894, also in *The Engineering Magazine*, December, 1894. It would seem that in most cases a small gas or oil engine would be preferable to a windmill for driving a dynamo, since the plant for a given capacity would be less costly and complicated and much more reliable; it being a fact that it requires a very large windmill to develop sufficient power for even a small plant. Nevertheless, for country residences the windmill might be considered more desirable; but the objectionable features of the gas or oil engine could usually be avoided by placing it in a shed or building at some distance from the house. The perfect safety of the windmill is, of course, one of its special advantages.

The table on the opposite page, taken from an article by Mr. George H. Morse,* gives detailed figures concerning cost, output, efficiency, and other data of windmill plants.

For further information in regard to water-power and windpower, reference may be made to the following books and articles.

Hydraulic Motors, by G. R. Bodmer; Second Edition, N. Y., 1895.

Theoretical Mechanics, byWeisbach. Translated by Coxe, Eighth Edition, NY., 1889; Vol. II., Part I., Hydraulics and Hydraulic Motors.

Development and Transmission of Power, by W. C. Unwin, London, 1894.

Construction of Mill Dams. Published by James Leffel & Co., Springfield, Ohio.

* "Windmills for Electric Lighting," *Electrical World*, June 10, 1893.

Table Showing the Cost of Electric Lighting by Wind Power.

Diameter of wind-wheel in feet.	Cost of geared windmill, shafting, and tower.	Useful horse-power developed. Wind sixteen miles per hour.	Average number of hours this horse-power will be developed per day.	Expense of power, cents per hour.				Watts recovered from dynamo, 50% efficiency.	Cost of dynamo.	Expense of generating electricity.			Watt-hours recovered from accumulators per day. Efficiency 45%.	Number of lamps, 16 c.p., 110 volts.	Number of hours lamps will run per day.	Required capacity of accumulators in ampere hours.	Cost of 58 accumulator cells.	Cost of automatic battery regulator.	Expense of storing the electricity.			Total expense of obtaining electricity per hour.	Total cost of the eight hours' daily storage.	Equivalent number of lamp-hours.	Average cost of lamp-hour from wind-power in cents.
				Interest on first cost at 5% per annum.	Depreciation at 5%.	Attendance.	Oil.			Interest on first cost.	Depreciation at 5%.	Oil.							Interest on first cost.	Depreciation at 20%.	Attendance of plant.				
8½	$153	0.04	8	0.26	0.26	0.06	0.04	14.9	$15	0.03	0.03	0.05	53.7	1	0.84	4	$21	$20.00	0.07	0.28	0.24	1.32	10.56	0.84	12.57
10	164	0.12	8	0.28	0.28	0.06	0.04	44.8	20	0.03	0.03	0.05	161.1	1	2.52	4	21	20.00	0.07	0.28	0.24	1.36	10.88	2.52	4.32
12	177	0.21	8	0.30	0.30	0.06	0.04	78.3	25	0.04	0.04	0.06	279.6	1	4.38	5	27	20.00	0.08	0.32	0.24	1.48	11.84	4.38	2.70
13	181	0.25	8	0.31	0.31	0.06	0.07	93.2	30	0.05	0.05	0.06	335.7	1	5.26	6	32	20.00	0.09	0.36	0.24	1.60	12.80	5.26	2.43
14	227	0.28	8	0.39	0.39	0.06	0.07	104.4	30	0.05	0.05	0.06	376.0	1	5.89	7	37	20.00	0.10	0.40	0.24	1.81	14.48	5.89	2.46
16	301	0.41	8	0.51	0.51	0.06	0.07	152.9	40	0.07	0.07	0.10	550.5	2	4.31	10	54	20.00	0.12	0.48	0.24	2.23	17.84	8.62	2.08
18	370	0.61	8	0.60	0.60	0.06	0.07	227.5	50	0.08	0.08	0.10	1,433.4	5	4.49	26	124	20.00	0.25	1.00	0.24	3.08	24.64	22.45	1.10
20	373	0.79	8	0.64	0.64	0.06	0.10	279.7	60	0.10	0.10	0.30	1,761.9	6	4.60	32	153	20.00	0.30	1.20	0.24	3.68	29.44	27.60	1.07
22	544	1.23	8	0.93	0.93	0.06	0.10	458.8	130	0.22	0.22	0.30	2,890.4	10	4.53	52	249	20.00	0.46	1.84	0.24	5.30	42.40	45.30	0.94
25	584	1.34	8	1.00	1.00	0.06	0.10	499.8	140	0.24	0.23	0.40	3,148.9	12	4.11	57	273	20.00	0.50	2.00	0.24	5.78	46.24	49.32	0.94
30	679	2.40	8	1.16	1.16	0.06	0.13	895.2	175	0.30	0.30	0.40	5,639.8	20	4.42	103	470	20.00	0.84	3.36	0.24	7.95	63.60	88.40	0.72
36	743	2.95	8	1.27	1.27	0.06	0.13	1,110.3	210	0.36	0.36	0.50	6,932.2	25	4.34	125	571	20.00	1.01	4.04	0.24	9.24	73.92	108.50	0.68
40	842	4.42	8	1.44	1.44	0.06	0.13	1,648.7	270	0.46	0.46	0.50	10,386.6	38	4.30	190	868	20.00	1.52	6.08	0.24	12.33	98.64	163.40	0.60
50	1,592	6.88	8	2.73	2.73	0.06	0.16	2,566.2	300	0.51	0.51	0.60	16,167.3	60	4.22	294	1,278	20.00	2.22	8.88	0.24	18.64	149.10	253.20	0.59
60	1,902	10.00	8	3.26	3.26	0.06	0.16	3,730.0	400	0.68	0.68	0.80	23,499.0	85	4.33	427	1,857	20.00	3.21	12.84	0.24	25.19	201.50	368.00	0.55

"Central Stations Operated by Water Power," a paper before National Electric Light Association, September, 1891, *Electrical Engineer*, Sept. 16, 1891.

"Steam *vs.* Water Power," Samuel Webber, *Iron Age*, May 11, 1893.

"Cost of Steam Power, etc.," (Appendix on Water Power), Dr. C. E. Emery, *Trans. Amer. Inst. Elec. Eng.*, March, 1893.

"Water Power, Its Generation and Transmission," Samuel Webber, *Trans. Amer. Soc. Mech. Eng.*, Dec. 1895.

The Windmill as a Prime Mover, by A. R. Woolf, New York, 1890.

"Charles F. Brush's Windmill Accumulator Plant," *Electrical Engineer*, Dec. 24, 1890, from *Scientific American*, Dec. 20, 1890.

"Wind Power for the Generation of Electricity," *Electrical Engineer*, Aug. 31, 1892.

"Windmills for Electric Lighting," George H. Morse, *Electrical World*, June 10, 1893.

"Windmills for Electric Lighting," *Electrical World*, Feb. 3, 1894.

"The Windmill Electric Lighting Plant at Marblehead," *Electrical Engineer*, Nov. 21, 1894.

"Generating Electricity by Windmills," I. N. Lewis, *Engineering Magazine*, December, 1894.

The catalogues of the various manufacturers of water-wheels and windmills give a great deal of definite information in regard to these subjects.

CHAPTER XV.

MECHANICAL CONNECTIONS BETWEEN ENGINES AND DYNAMOS.

DIRECT COUPLING, BELTING, AND SHAFTING.

VARIOUS means are employed to connect the engine or other prime mover with the dynamo, of which the following are the most important: —

1. Direct coupling.
2. Belting (flat).
3. Rope driving.
4. Toothed gearing.
5. Friction gearing.
6. Peculiar forms of connection, such as magnetic and hydraulic gearing.

Other apparatus, such as shafting, clutches, hangers, pulleys, etc., are used in connection with the above-named methods.

Direct Coupling. — This is the simplest, and for that reason the most desirable, means of connection, provided it can be carried out without involving sacrifices which offset its advantages. The direct coupling of an engine and dynamo compels them to run at the same speed, and gives rise to certain difficulties, for the reason that the natural and most desirable speeds of the two machines do not usually agree. The ordinary rule for the speed of a dynamo is that the peripheral velocity of the armature should be about 3,000 feet per minute. Therefore an armature 1 foot in diameter should run at about 1,000 revolutions per minute. This value is not absolute, and it is perfectly possible to operate armatures at considerably higher or lower speeds; but experience seems to show that this speed gives satisfactory results in most cases. A higher speed tends to cause vibration, strains, and wear, and in the long run is not economical. A lower speed simply means that the output of the dynamo is reduced in direct

proportion to the speed; that is, a dynamo run at 500 revolutions which is perfectly capable of running at 1,000 develops only one-half as much electrical power as it is really able to give, and is therefore not doing its full amount of work. This fact is more fully set forth in connection with low-speed dynamos. (Chapter XVII.)

The speed of a steam-engine, on the contrary, is naturally and properly quite low; and even a high-speed steam-engine cannot be run above 350 revolutions per minute advantageously (page 161), and a speed of 75 to 100 revolutions per minute is a much better limit for engines of any considerable size. The large Corliss engines used in electric lighting with such excellent results run at about 60 to 125 revolutions per minute. Thus we see that the ordinary steam-engine and dynamo do not naturally agree in speed; and it is necessary either to raise the speed of the engine above the point at which it works well, or reduce the speed of the dynamo below that at which it gives its full capacity, in order to make the two coincide, and permit them to be directly coupled. As a matter of fact, one or both of these modifications in speed are made in almost all cases of direct coupling; and the engine is run higher, or the dynamo run lower, in speed than would be the case if the two machines were to operate independently. The running of an engine above a certain speed is decidedly objectionable; since it reduces its efficiency, requires more attention, increases the wear and repairs, and consumes more oil. Any one who has ever had experience in running engines at 80 revolutions per minute, and also at 350 revolutions per minute, realizes the enormous difference between the two cases in what might be called the *comfortable*, as well as the economical, working of the plant. In fact, any increase in speed of an engine, even if it is only 10 or 20 per cent above that at which it runs normally, will begin to make very perceptible differences in its working.

The speed of a dynamo, on the other hand, can be brought down without much reduction in efficiency or other disadvantage, except that the output is decreased, or, what is the same thing, the size and weight are increased for a given output. It is a common thing to hear persons attempt to get around this fact, and confuse or deceive themselves by assuming some form of

winding or other arrangement which will give the same output at a lower speed; but we know that a dynamo running at 250 revolutions per minute will give almost exactly twice the output if the speed be increased to 500 revolutions per minute, and in many cases there would be no reason why the higher speed would be objectionable. In other words, it is run at a low speed, and has a diminished output, simply to allow it to be directly coupled to the engine. It may be a proper, or even a very desirable, thing to design dynamos to work at low speed; but the engineer should fully realize that it usually involves some sacrifices of output and efficiency in the machine itself. The usual way to construct a low-speed dynamo is to make the armature of large diameter, thus securing a sufficiently high peripheral velocity; at the same time the armature core is made in the form of a ring, with a comparatively small radial thickness, in order to reduce the weight of iron required. Nevertheless, the frame, shaft, bearings, and other parts of such a machine are necessarily heavier and more costly than if the armature were of smaller diameter and higher speed. The compactness, simplicity, and general advantages of direct coupling are so great, however, that they will often fully warrant the extra cost; and in some cases it may be almost a necessity, as, for example, in the case of a dynamo for use on shipboard, or for other plants in which the space is very limited.

The direct coupling of dynamos with turbines can be carried out without departing from the normal speed of either machine; that is to say, the ordinary speed of a turbine agrees well with the normal speed of a dynamo of corresponding power. The shaft of a turbine, however, is usually vertical, while that of the dynamo is horizontal; hence, in order to directly couple them, one or the other must be changed from its ordinary arrangement. This can be done either by constructing a dynamo to revolve on a vertical shaft, or a turbine with a horizontal shaft (Fig. 71) can be obtained. These latter may easily be directly coupled with a dynamo. If the armature is mounted directly upon the shaft of a vertical turbine, the aggregate weight becomes large, and difficult to support. A step-bearing at the bottom is not adequate to carry the weight, and will cause much trouble from heating, except in a very small plant. A number of thrust-bearings

arranged at various points on the shaft may distribute the pressure sufficiently to carry it properly; but in a large and important plant it is desirable to take a portion, or all, of the weight off of the bearings, either by magnetic attraction, or by causing the upward pressure of the water in the turbine to balance the weight, the latter plan being adopted for the 5,000 horse-power turbines at Niagara. Sufficient magnetic attraction might be obtained from the action of the field-magnet upon the armature of the dynamo. A toothed armature, for example, requires a force many times greater than its own weight to pull it even slightly out of the field. It may be preferable, however, to have a special magnet for the purpose, to avoid reducing the field flux. Devices of this latter kind have been constructed by the Oerlikon Works of Switzerland; one of which magnetic counterweights described in the *Electrical Engineer* (New York) of Aug. 22, 1894, balances a load of 30,000 lbs., consisting of a 600 horse-power turbine and dynamo, the consumption of electrical energy being only $\frac{1}{3}$ horse-power per ton, or $\frac{5}{6}$ of 1 per cent. The magnet which is fixed, is circular in form, and multipolar. It acts upon a flat ring armature attached to the shaft, and made of iron ribbon to prevent the generation of eddy currents. Provision is made for varying the attracting force.

In actual practice dynamos are not very often directly coupled to turbines, the connection being usually made by some arrangement of gearing and belting. It seems unfortunate, however, to lose the great advantages of direct coupling when the speeds agree so closely, provided that it can be accomplished by the use of the hydraulic or magnetic method of balancing the weight, or in any other reasonable way.

The direct coupling of an engine and dynamo is carried out according to several different plans, the simplest of which consists in mounting the armature of the dynamo directly on one end of the shaft of the engine; or two armatures may be carried, one on each end of the engine-shaft, making a double dynamo, as represented in Fig. 59. These plans have the advantage of not requiring additional bearings or any form of coupling.

Another arrangement consists in having a single long bearing, in which revolves the main shaft, carrying the armature on one end and the crank on the other. This has the advantage that

both the armature and crank, as well as the other moving parts, are on the outside and accessible; but the objection to it is that a single bearing does not usually run very well, and is apt to wear, because the length of the support is not as great as if two bearings were used.

The method of directly connecting engine and dynamos represented in Figs. 74 and 58 is both compact and substantial. It consists in extending the shaft of the engine, and mounting the armature upon it, as in the preceding cases; but a third bearing is added on the outside of the dynamo, which gives better support to the shaft, and enables the armature and commutator to be made of

Fig. 74. Direct-connected Engine and Dynamos.

any desired length, whereas if the armature overhangs, it must be made very flat. The mounting of all three bearings on a cast-iron base, as shown in the figure, secures great strength and permanency of alignment.

Still another common form of direct coupling is that in which an engine and a dynamo, each complete in itself, and each having two bearings, are coupled together by some mechanical connection, which may be either rigid or slightly elastic or adjustable. In the former case, the two shafts are practically equivalent to a single shaft; in fact, they might be made in that form, but it would be very inconvenient in replacing or repairing either the engine or the dynamo, whereas the mere connecting of entirely distinct machines affords great advantages in this respect. It is

somewhat difficult to adjust three or four bearings exactly in line; nevertheless, it can be accomplished with care and good workmanship.

The interposition of a coupling having more or less flexibility avoids the necessity for adjusting the bearings of both machines perfectly in line, and also the serious difficulties which arise if any of the bearings settle or wear more than the others. There are numerous forms of such flexible or adjustable couplings, one of which is made by the builders of the "Straight Line" engine,* but is only capable of slight adjustment. Another device, which would allow for very imperfect alignment of the two shafts, is represented in Fig. 75, and consists of two disks, one rigidly mounted on each shaft. Both disks are provided with pins *P* and *N*, which are connected by springs *S*; but the pins *P* of one disk are farther from the shaft than the pins *N* of the other disk, so that they clear each other: hence, when a short circuit or a sudden stoppage of either the dynamo or the engine occurs, and the springs are thereby broken, the other machine can continue to revolve freely.

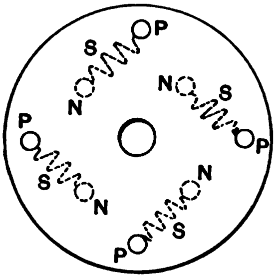

Fig. 75. Flexible Coupling for Engine and Dynamo.

The Raffard coupling, which is commonly employed in France in connection with dynamos, employs stout rubber bands passing around the pins instead of springs, which still further reduces the danger in case of accident.

An ordinary friction clutch (page 250) is one of the most convenient means for directly coupling a dynamo with an engine. It is easily applied, since it is especially designed and made to connect two shafts together; and it has the great advantage over almost any other coupling of being readily disconnected, so that the dynamos can be stopped without interfering with the engine; nevertheless, it is rarely used for this purpose.

The relative efficiency of belting and direct coupling depends greatly upon the conditions; but in general the former is more efficient at light loads, and the latter at or near full load. A careful test made at the Edison Station (Third District) in Brooklyn,

* *Electrical World*, Nov. 2, 1895, p. 503.

N.Y., showed that at about the full load of 250 horse-power the electrical output was 87 per cent of the total indicated horse-power for direct coupling, and 81 per cent for belting. At about one-third load they were both the same at 70 per cent; and at one-fifth load belting gave 60, and direct coupling only 35, per cent efficiency. The obvious conclusion from this test, which agrees with results obtained in other cases, is that direct coupling is (about 5 per cent) more efficient between one-half and full load, but below one-third load belting gives higher efficiency, and for very small loads it may be far more efficient than direct coupling. If in electric lighting the plant runs at light loads for a large portion of the time, as is often the case, belting would be more economical than direct coupling.

BELTING.

If the dynamo is not directly coupled to the source of power, it is usually connected by some form of belting. In fact, until within a short time belting was almost the only means employed for this purpose. The simplicity, compactness, and positive action of direct coupling have caused it to become the most approved method; and for that reason belting has become somewhat unpopular by comparison, and is often spoken of as if it were actually bad practice. Nevertheless, the good service it has rendered ever since the introduction of the dynamo, its very extensive use all over the world at the present time, and the fact that it is actually preferable in many cases, make it well worthy of careful and favorable consideration. In the experience of the author, belting, if properly arranged in the first place, and if given reasonable attention, runs very satisfactorily in most cases; and the troubles or unsatisfactory results which are obtained from it are usually the direct results of incorrect design or careless working. The use of peculiar and complicated forms of belting is responsible for a great deal of its unpopularity, when, as a matter of fact, it is simply bad engineering on the part of the designer of the plant. A plain, flat belt, made of the best quality of strong and pliable leather, will work well in almost every case if properly arranged and attended to; and other forms of belting, particularly rope-driving, operate very successfully under suitable conditions.

The advantages of belting in general are: —

1. It enables almost any desired ratio of speed to be obtained in a convenient and simple manner.

2. It is cheap.

3. It is applicable to almost any case, provided the space is sufficient.

4. The machines are almost entirely independent, so that either the engine or dynamo, or both, can be changed, repaired, or operated without interfering with each other.

5. The dynamo is perfectly insulated so far as the belting is concerned, since the latter is almost always made of non-conducting material.

6. In case of a short circuit or other accident, the belt will slip, and act as a safety-valve, so to speak, and may thereby avoid serious trouble.

The general disadvantages of belting are: —

1. It requires considerable space, since the machines must be placed a certain distance apart in order to make the belt work properly.

2. The action is not positive, there being a certain slip even in normal working, and in case of an over load or other trouble the belt may run off the pulleys, or break.

This last has been given above as an advantage; and in point of fact it may be looked upon as an advantage or disadvantage, according to circumstances, positive action being, of course, ordinarily desirable: but in case of accident the relief given by the belt may ultimately avoid serious consequences to the engine or dynamo.

3. Belting is somewhat unsteady in its action, and is likely to cause slight fluctuations in the speed and voltage of dynamos on account of its slipping or flapping. This is decidedly objectionable, particularly in incandescent lighting; but it can usually be avoided by proper design.

4. Belting produces a certain amount of noise which is not at all loud, but might be objectionable in some cases, and might be a reason for the adoption of direct coupling.

5. Belts exert a side pull on the bearings which not only produces loss of power by friction, but also tends to wear the latter. As a matter of fact, however, there are many dynamos which have been running for years without showing any considerable wear from this cause.

The following table shows the principal kinds of belting that may be employed, each of which will be taken up and treated separately in the order given.

Rope belting is included with flat belting under the general heading, since they are similar in their action and application.

KINDS OF BELTING.

1. LEATHER (flat) { Plain, Perforated, Link.
2. RUBBER (flat).
3. COTTON (flat).
4. COTTON-LEATHER (flat).
5. ROPE { Hemp, Cotton, Raw hide.
6. WIRE ROPE.
7. WIRE SPRING.
8. CHAIN AND SPROCKET WHEELS.
9. MAGNETIC BELTS.

Plain Leather Belting. — As already stated, this is usually the most reliable and satisfactory belt for general use. The best quality of leather is required for belting, and should be carefully selected and treated. The process by which the hides are tanned and made into belts is fully described in a paper entitled, "From the Tannery to the Dynamo," read by C. A. Schieren, before the National Electric Light Association, Feb. 24, 1892.

There are three standard thicknesses of belting, — single, light-double, and double. For driving dynamos or other high-speed machinery, the "light-double" belting is usually the best.

The exact amount of power that a given belt is capable of transmitting is a matter that is not very definite, since engineers adopt different rules and practices. The ordinary rule is that a "single" belt will transmit 1 horse-power for each inch in width at a speed of 1,000 feet per minute. If the speed is greater or less, the power is correspondingly increased or decreased.

This is based upon the condition that the belt is in contact with the pulley around one-half of its circumference, or 180°, which is usually the case. If the arc of contact is less than half a circle, the power transmitted is less in the following proportion: An arc of contact of 135°, or three-eighths of the whole circumference, gives .84, while 90° gives only .64 of the power derived from a belt-contact covering one-half of the periphery.

If, on the other hand, the upper side of the belt sags downward, which is always desirable, and the belt is in contact with more than half of the circumference of the pulley, then the grip

is considerably increased, the belt acting on the principle of a strap-brake. The greatly increased power that can be transmitted when the belt thus surrounds more than half of the pulley makes it very desirable to have the *loose side of the belt on top*. If the loose side is below, it sags away from the pulleys, and is also likely to strike the floor.

The complete expression is H. P. $= \frac{W \times S \times C}{1000}$; that is, the horse-power transmitted by a "single" belt is equal to the width of belt in inches (W) multiplied by the speed of belt in feet per minute (S), and by the figure depending upon the arc of contact (C), and divided by 1,000. For example, a belt six inches wide traveling at 1,500 feet per minute, and touching three-eighths of the circumference of the pulley, will transmit:—

$$\frac{6 \times 1500 \times .84}{1000} = \frac{7560}{1000} = 7.56 \text{ H. P.}$$

"Double" belting is expected to transmit one and one-half, and "light-double" one and one-quarter, times as much power as "single" belting. Another rule for calculating the power that a single belt will convey is that 75 square feet per minute passing over the pulley transmits one horse-power.

Belting formulas are only approximate, and should not be applied too rigidly; since the grip of the belt upon the pulley varies considerably under different conditions of tension, service, moisture in the atmosphere, etc.

The smooth side of a belt should always be run against the pulley, as it transmits more power, and is more durable. The common idea that the rough side of a belt "has more friction" is entirely erroneous.

Dynamo or other high-speed belts should be made "endless" for permanent work; but they may be used with laced joints temporarily. It is best to order an endless belt of the right length from the manufacturer; but if necessary it may be spliced by any one of ordinary skill. Both ends of the belt are pared down on one side with a sharp knife, into the form of a long, thin wedge, so that when laid together a long uniform joint is obtained of the same thickness as the belt itself. The parts are then firmly joined by cement and rivets. Staples or screws made of

wire are often used instead of the ordinary copper rivets, in order to leave the surface of the belt perfectly smooth. It may be necessary to splice or lace a belt while in position on the pulleys; and for that purpose some form of belt-clamp, such as shown in Fig. 76, should be employed.

If a belt is ordered to be made endless, or is spliced away from the pulleys, great care should be exercised in measuring the exact length required. A string that will not stretch, or a wire put around the pulleys in the position to be occupied by the belt, is the best means to avoid a mistake. In measuring for a belt, the dynamo should be moved on its sliding base so as to make the distance the shortest, in order to allow for the stretch of the belt, which usually amounts to from $\frac{1}{4}$ to $\frac{1}{2}$ inch per foot.

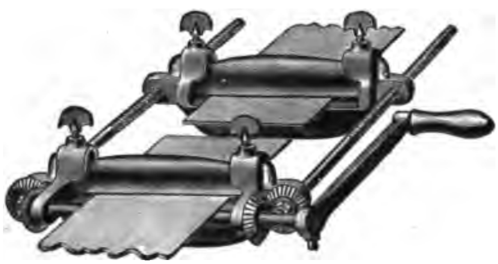

Fig. 76. Belt Clamp.

The lacing of a belt is the simplest and most common method of making a joint. At high speeds, however, a laced joint is apt to pound on the pulleys, producing noise, and also flickering in incandescent lamps; nevertheless, its simplicity and reliability make it perfectly allowable in an emergency or for temporary use.

In lacing belts the ends should be cut perfectly square, and there should be as many stitches of the lacer slanting to the left as there are to the right; otherwise, the ends of the belt will shift sideways, owing to the unequal strain, and the projecting corners may strike or catch the clothing of persons. Two good ways of accomplishing this are shown in Fig. 77. In plan A two rows of holes should be made with a punch, as indicated. The nearest hole should be $\frac{3}{4}$ inch from the side, and the first row $\frac{7}{8}$ inch from the end, and the second row $1\frac{3}{4}$ inch from the end of the belt. In large belts these distances should be a little

greater. A regular belt-lacing (a strong, pliable strip of leather) should be used, beginning at hole No. 1, and passing consecutively through all the holes as numbered.

In plan B there is only a single row of holes. This plan has the advantage of making the lacers lie perfectly parallel to the motion on the pulley side. The lacing is doubled to find its middle; and the two ends are passed through the two holes marked "1" and

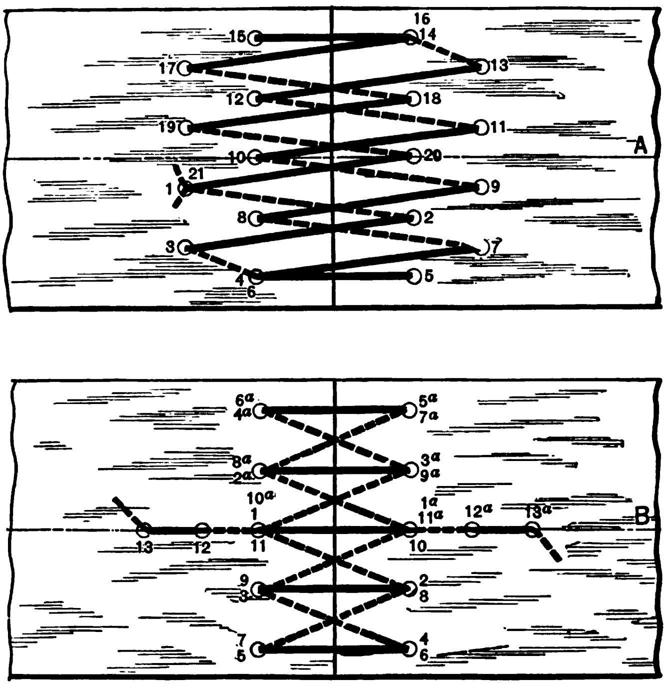

Fig. 77. Methods of Lacing Belts.

"1*a*," precisely as in lacing a shoe. The two ends are then passed successively through the two series of holes in the order in which they are numbered, 2, 3, 4, etc., and 2*a*, 3*a*, 4*a*, etc., finishing at 13 and 13*a*, which are additional holes for fastening the ends of the lacer.

In both diagrams the solid lines represent the lacing on the side against the pulley, and the dotted lines the other side. In making either a cemented or laced joint, great care should be ex-

ercised in order that it should be perfectly straight, as a crooked belt is unsightly and runs very badly.

Belt hooks or studs are often used instead of lacing; but they have little advantage over the latter, except that they are a little more easily put in, and they are not generally to be recommended for dynamo belts.

Perforated belts are often used for the reason that a film of air is likely to be imprisoned between the belt and the pulley, and prevent a good contact. There is every reason to believe that this does actually occur at high speeds, such as three to five thousand feet per minute, which are the ordinary limits for dynamo belts. The simple experiment of putting two smooth and flat boards together will prove that it takes an appreciable time for the air between them to escape and permit perfect contact. Small perforations are therefore made in the belt, to allow the air to escape; and since they are in the form of narrow slits, with their longest dimension in the direction of the length of the belt, they do not materially reduce its strength.

Arrangement and Care of Belting. — It is very desirable, for satisfactory and efficient running, that belts should be of reasonable length and nearly horizontal. If it is absolutely necessary to connect pulleys at different levels, the belt should be as nearly horizontal as possible, and should make an angle of at least 45° with the vertical, if possible; otherwise it will not be likely to work well. The distance between the centers of two belt-connected pulleys should be at least three times the diameter of the larger pulley, and it may well be four times if the space permits. The belt should be just tight enough to avoid slipping, without straining the shaft or bearings. A new belt will not carry as much power as one which has been properly used for a few months.

The dynamo shaft and the shaft to which it is to be belted must be placed perfectly parallel, and the centers of the two pulleys must be exactly opposite to each other, in a straight line perpendicular to the shafts. The machine should then be turned slowly with the belt on, to see if the latter tends to run to one side of pulley, which would show that it is not yet properly "lined up;" and in this case the machine should be slightly moved, until the belt runs in the middle of the pulleys, and does not tend to work to one side. If possible, the machine and belt

should be set and adjusted so as to cause the armature to move back and forth in the bearings while running, on account of side motion of the belt, and thus make the commutator wear smoothly, and distribute the oil in the bearings, — except in certain machines in which the pole-pieces are at the ends of the armature.

Fig. 78. Link Belt.

It is always desirable to have belts as pliable as possible; hence the occasional use of some good belt-dressing is desirable. Rosin and other sticky substances are sometimes applied to increase the adhesion; but this is a practice which is only allowable in an emergency.

In places where they are likely to catch in the clothing of any person, belts should be inclosed in a casing or railing.

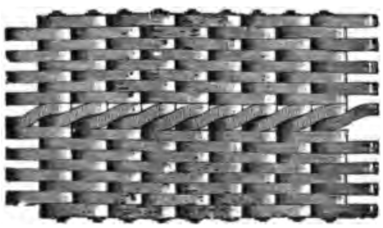

Fig. 79. Link Belt.

Link Belts. — These consist of small links of leather about $\frac{3}{4}$ inch wide, 2 inches long, and $\frac{1}{4}$ inch thick, joined together by iron bolts in the manner represented in Fig. 78. Each iron bolt only runs half-way through the belt, the two halves of the belt being held together by the row of diagonal links in the middle, as shown in Fig. 79, which form a hinge that permits the belt to adjust itself to the crowning of the pulley. The advantages claimed for a link belt are that it can be run with the upper side drooping so that it surrounds a large portion of the circumference

of the pulley, thus securing a good grip upon it; and a link belt can easily be joined to form an endless belt, or it can be lengthened or shortened readily by putting in or taking out links. Link belts have, however, several disadvantages which are quite serious: —

1. They are very heavy, being three or four times the weight of the same length and width of ordinary belting, and are therefore difficult to put on or take off the pulleys, and produce great strain on the bearings.
2. They have ragged edges, with projecting nuts, which are likely to catch in the clothing or flesh of persons.
3. If they accidentally break or run off of the pulleys, their great weight and rough edges would be likely to produce far more serious injury than a simple leather or cotton belt.
4. They cost two to three times as much per foot as the same width of plain leather belting.
5. They emit while running a peculiar rushing sound, which is more objectionable than the noise made by an ordinary belt.

The greatly increased grip, and capacity to transmit power, which are claimed for link belts are very doubtful. It may be a fact that for a given length and width they have a somewhat greater grip on the pulley than ordinary belts: but it should be remembered that their weight, and consequently the drag on the bearings, is three or four times as great; hence there is more strain on the bearings for the same power transmitted. It is fair to state that a link belt can be run with a much greater sag on the upper side, so that the arc of contact with the pulleys is increased. This is made possible by the fact that the path of a link belt is a smooth, graceful curve, without the objectionable flapping which occurs when an ordinary belt is very loose. Nevertheless, the weight of any belt must all be carried by the two bearings, and the fact that the link belt is used with more sag does not make up for its excessive weight.

The link belt is often recommended for places where the distance between the shafts is not sufficient to allow an ordinary belt to work well, in which case the extra weight of the former is an advantage. In fact, it is evident that the distance between centers should be less for a link belt, and that it is a mistake to follow ordinary practice in this respect.

Rubber Belting has the following advantages: —

1. It has a good grip upon the pulley.
2. It is waterproof.

The disadvantages of rubber belting are:—

1. It is expensive, costing two or three times as much as an equivalent leather belt.

2. It is not as strong as a leather belt; that is, its tensile strength is considerably less.

3. It is not as durable as a leather belt, and will not last more than about one-half as long under ordinary circumstances.

4. It will not stand any heating which might be caused by a hot pulley, bearing, or even a very warm engine-room.

5. In case it slips upon the pulley because of a short circuit, or other reason, a rubber belt will be seriously injured by having its surface torn or worn away, and also by the heat resulting from the friction, whereas a leather belt is far less likely to be injured.

6. A rubber belt cannot be easily spliced or laced. This last fact is often a serious disadvantage; for although endless belts are always preferable on dynamos, there are many times when a laced joint can be made for temporary use, and if desired a smooth splice can be made in a leather belt without much difficulty, thereby making it endless. A rubber belt, on the other hand, is made endless by its manufacturer, and cannot be subsequently shortened, or have a joint made in it, by a person possessing ordinary skill and facilities. This inability to make joints usually renders it necessary to entirely renew a rubber belt if it is injured at any point, whereas a leather belt could be slightly shortened, or a new piece might be put in.

The conclusion derived from the above statements, and from general experience, would indicate that the slight increase in grip given by a rubber belt does not make up for its numerous disadvantages, particularly those of high first cost and lack of durability, except under particular conditions. The principal case in which a rubber belt would be desirable is when it is exposed to moisture; and then a rubber belt would work as well as, or even better than, in a perfectly dry place. In fact, a rubber belt could actually be run under water. A leather belt, on the contrary, is injuriously affected by moisture, both its grip and its durability being greatly reduced.

Cotton Belting. — Belts made of cotton, which are similar to stout canvas in appearance and texture, are often used for driving dynamos and for other purposes. They possess the advantages of cheapness and lightness, and will stand slipping with even less injury than leather belts; since they do not tend to have their surface torn, and the heat produced by the friction would not affect them until a high temperature is reached. They also run more smoothly, and make less noise, than leather belts.

Cotton belts are inferior to leather in tensile strength, durability, and grip upon the pulley; and in most cases it would not seem that the advantages would counterbalance the disadvantages. Many engineers, however, prefer cotton belts to any other; and since there is no radical objection to them, and the experiment of trying them can be made with little expense, there is no reason to condemn them.

Cotton-leather belts are those in which one side or surface is made of cotton, and the other of leather; and they are intended to combine the advantages of both, the leather side being run against the pulley in order to secure the grip and durability which it possesses, and at the same time the lightness, cheapness, and smooth running of cotton belting. It is a fact, however, that these belts are not as durable as plain leather, and it is a question whether they are so generally satisfactory and reliable. In certain cases, however, they have been found to give better results than any other kind of belting. For example, in some of the Edison central stations, where the belts run almost vertically upward from the engines to the dynamos, it was found, after long trial of various kinds of belting, that cotton-leather gave the best results. This is probably due to the fact that in this case the grip upon the pulley was obtained by actual tension, and the elasticity of the cotton-leather belt was an advantage.

A horizontal belt, on the other hand, does not require actual stretching, but should obtain the necessary friction by a reasonable weight, due to a certain length, which causes the upper side to sag, and secure a large arc of contact. In this case the elasticity of the cotton belt, as well as its lightness, would be positively objectionable; whereas in a vertical belt both of these qualities appear to be desirable. The general conclusion would seem to be that cotton-leather, or other elastic material, may be preferable in a vertical or short horizontal belt which must obtain its grip by tension, and that ordinary leather is better for horizontal belts of reasonable length and weight.

ROPE-DRIVING.

The use of rope for connecting engines and dynamos has been common in Europe for many years, but it has not been used to

any great extent in America until quite recently. It possesses, however, certain marked advantages, and is thought by many engineers to be decidedly preferable to leather belting. The rope runs in V-shaped grooves in the peripheries of the pulleys, and thereby obtains great grip by a sort of wedging action. The kinds of rope ordinarily used for this purpose are cotton, hemp, and rawhide, each of which has certain merits, and has been successfully used.

The advantages of rope-driving are: —

1. It is cheap.
2. It is durable.
3. A large power can be transmitted with a given diameter and width of pulley, on account of the grip obtained by the rope in the V grooves.
4. It is almost noiseless, being in this respect preferable to any other kind of belting.
5. Ropes can be used by reason of their lightness to transmit power where the distance may be great (a hundred feet or more), in which case no other form of belting would be applicable.
6. Rope belting can also be employed to connect an engine and dynamo when they have to be put very close together in order to save space, since the grip is greatly increased by the wedging action.
7. A rope belt usually shows the effects of wear before there is much danger of breaking, provided the splices are well made.

The first of the above advantages — cheapness of the rope itself — is offset more or less by the fact that grooved pulleys cost more than those for a flat belt, and the total cost is about the same.

The fifth and sixth of the above advantages may appear to be contradictory, but they can be easily explained. The possibility of transmitting power a considerable distance by rope is obvious, and is due to the lightness of the rope. In fact, it is sometimes stated that rope belting should only be used when the distance between the pulleys is at least fifty to one hundred feet, in order that there may be sufficient weight to give the required grip. It is evident, however, that this grip may also be secured, no matter how short the distance may be, by actual tension, which may be obtained by the belt-tightening device of the dynamo. In actual experience with rope-driving, where the distance between the pulleys was very considerable, and also where it was very small, the results in the latter case were far better than in the

former. When the pulleys are close together and the rope is tight a perfectly steady action is obtained; whereas, if the pulleys are far apart, the great length of the rope allows of considerable stretching and taking up of slack when the load suddenly increases on the dynamo, which momentarily reduces the speed and voltage of the latter, and produces a disagreeable flicker in the lamps. This was so serious in one case as to necessitate moving the dynamo closer to the engine. This difficulty would seem to be inherent in either long or elastic belts. If a long belt is necessary, this trouble might be overcome by the use of wire rope, which would stretch very little, and in which any slack could be avoided by supporting the rope at numerous points on idle pulleys.

Elasticity or slack in a belt will tend to eliminate fluctuations due to the engine; but, on the other hand, it allows variations in voltage to occur if the load on the dynamo changes suddenly.

The various kinds of rope used for driving dynamos are made of manilla hemp, cotton, rawhide, or wire (iron or steel). The chief advantage of manilla rope is that its breaking strength is high, being from 7,000 to 12,000 lbs. per square inch. This value depends upon the quality and upon the amount of twist. Increasing the latter decreases the strength, but makes the rope more solid and durable. Cotton rope has only a small fraction of the strength of a manilla rope, having only one-tenth the breaking-strength, according to Nystrom; but since a driving-rope usually transmits only about 3 to 5 per cent of its full tensile strength, this is less important than other considerations. The advantages of cotton rope for this purpose are, greater flexibility, which permits of the use of smaller pulleys; less internal wear and loss of power due to the bending of the fibers; and greater softness, so that any enlargement in the rope itself or in the splice will be compressed, until the rope is of practically uniform size. The bending and sliding of the fibers and strands upon each other cause internal wear in a rope, and may be more injurious than the external wear against the pulley. This wear is reduced by lubrication; and while this diminishes the strength 20 to 30 per cent, according to Flather,* it is less objectionable than the wear. In fact, the greater stiffness and roughness of the fiber of manilla rope cause so much internal wear that it may not last as long

* *Electrical World*, vol. xxiii. p. 179.

as a cotton rope under the same conditions, in spite of its far greater original strength.

Rawhide rope is supposed to have greater durability than manilla or cotton; but if it slips on the pulley, which it is likely to do occasionally in case of a short circuit or overload, the leather will be burned, and lose its flexibility, strength, and adhesive qualities. The cost of rawhide rope is fully five times as great as that of a good quality manilla rope, it is much more difficult to splice, and the joint is more likely to pull out; hence it is very doubtful if it should be selected except where it is exposed to moisture.

Wire rope is not very suitable for driving dynamos, because it is too stiff to bend around the small pulleys ordinarily used on these machines. It might be employed, if properly arranged, where the dynamo has to be placed at a considerable distance from the prime mover, as is sometimes the case with water power; and the fact that it is not affected by water makes it suitable for out-door work.

Wire springs are used with grooved pulleys to drive small machines. They have the advantages of great flexibility and elasticity; but they do not transmit much power, and are rarely used except for hand dynamos.

Calculating the power transmitted by rope belting is somewhat uncertain, as in the case of flat belting. The coefficient of friction is given by Unwin * as .28 for a rope on a plain cylindrical metal pulley, and is stated to be .075 by Reuleaux. The first of these values is probably too high, and the latter too low. With ropes that are partly worn and sufficiently greased to wear well, this coefficient is taken as .12 by Flather, † and this is probably an average practical value. The wedging of the rope in the groove increases the friction, so that we have $f = .12 \text{ cosec. } \frac{a}{2}$, in which a is the angle between the sides of the groove, and is usually 45°: hence the coefficient becomes .31; that is, the effect of the groove is to augment the grip on the rope over two and a half times. The grip also depends upon the arc of contact. This is assumed by Flather to be 165° on the smaller pulley, which is an ordinary value. The effect of centrifugal force may be neglected at speeds

* *Elements of Machine Design*, p. 407. † *Electrical World*, vol. xxiii. p. 245.

below 2,000 feet per minute, but above that it must be considered; and at 8,500 feet per second it counteracts the whole of the allowable tension. The latter is assumed to have an ordinary value of 200 d^2 lbs., d being the diameter of the rope in inches.

For a complete discussion of this matter, reference may be made to the elaborate series of articles by J. J. Flather already

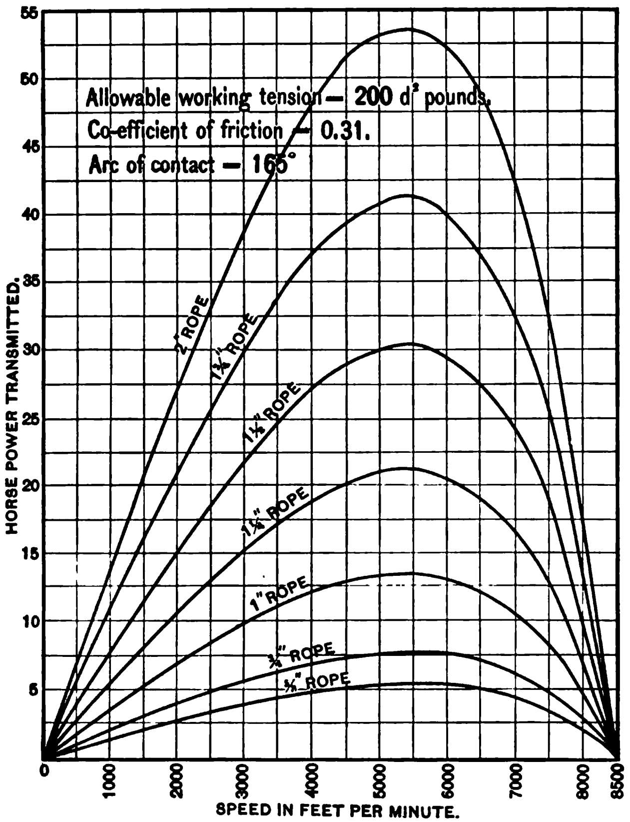

Fig. 80. Power Transmitted by Ropes.

quoted, which appeared in the *Electrical World* beginning Oct. 21, 1893. The curves shown in Fig. 80 give the general results of his calculations. The remarkable effect of centrifugal force is clearly shown, and also the fact that the maximum power is transmitted at 5,500 per minute, up to which point the increased speed gives greater power, but beyond which it causes excessive centrifugal force tending to lift the rope out of the groove.

Arrangement of Rope belting. — There are two methods of arranging rope transmission: one consists in using several separate belts; and the other employs a single endless rope, which passes spirally around the pulleys several times, and is brought back to the first groove by a slanting idle pulley. The former plan is often called the European, and the latter the American, or "wound" system; but both are employed in this country. The separate ropes do not require the carrying-over pulley, and if one rope breaks, the remaining ones are sufficient to transmit the power temporarily; whereas an accident with the single-rope arrangement would entirely interrupt the service. The carrying-over pulley is mounted in bearings which can be moved by a screw or weight so that it can be used as a belt-tightener; but since belt-driven dynamos are almost always mounted upon sliding bases, this advantage is not of so much value as in the case of other kinds of machinery. The chief difficulty with separate belts is the necessity for making several splices, and the fact that it is practically impossible to make and maintain the belts of exactly equal length; consequently they are of unequal tension, and hang at different lengths on the slack side, producing a very awkward appearance, even if it causes little difference in the actual working. The single rope is often supposed to have a perfectly uniform tension in all parts; but it is evident that if there is the slightest slip, the rope will be tighter in the first groove than it will be in the last: this variation is regular, however, and certainly is less unsightly than the very uneven sag of separate ropes.

Chain and Sprocket Wheel. — This form of mechanical connection consists of an endless chain of ordinary form which connects and fits on the peripheries of two wheels that are shaped or provided with pins to receive it. It is similar in principle to ordinary belting, but has the additional advantages of being *positive* in its action; that is, it allows no slip, and is unaffected by moisture: in fact, it could be run under water. To offset these advantages, sprocket-driving has the difficulty of being somewhat noisy; and the weight and centrifugal force of the chain, as well as the danger of its getting off of the sprockets, make it unsuited to high speeds. Nevertheless, it is a very effective device, and it is difficult to understand exactly why it is not used more than it is in connection with dynamos and other machinery.

Magnetic Belting. — Several devices of this sort have been suggested, but they are not in general practical use. One of the simplest forms consists of strips of sheet iron riveted at frequent intervals on an ordinary leather belt, and perpendicular to its length. Such a belt run with the iron strips outward on a magnetized iron pulley would be drawn against the pulley by magnetic attraction, thus increasing the friction or grip. The weight of the iron strips would produce considerable centrifugal force, tending to lift the belt off of the pulley at high speeds, and it would be rather troublesome to provide the pulley with a magnetizing coil and current; hence it is doubtful if this kind of belting is very practical.

Shafting. — An intermediate or counter-shaft is not desirable, since it increases the complication and friction losses; but it is often necessary in electric lighting, either to obtain a greater multiplication of speed than is possible by belting the engine directly to the dynamo, or to enable a single engine to drive a number of dynamos: as, for example, in arc-lighting stations.

The two important kinds of shafting are "cold rolled" and "turned." The former is rolled to the exact size, and requires no further treatment. It has the advantage of a smooth, hard surface, but is difficult to make perfectly true and straight; and if any portion of the surface is removed to make a key-way, for example, it is apt to cause the shaft to bend, owing to unequal internal strains. Turned steel shafting is most commonly employed, and has the advantage that shoulders, journals, or other variations in size, can easily be made in it. The following table gives the ordinary data of shafting: —

SHAFTING.

Diameter in Inches.	Weight. Lbs. per Ft.	H.P. at 100 Turns per Minute.	Average Net Price per Ft.	Width of Key-seat in Inches.
$1\frac{7}{16}$	5.5	4.3	$0.25	$\frac{3}{8}$
$1\frac{15}{16}$	10.	10.	.35	$\frac{1}{2}$
$2\frac{7}{16}$	15.8	20.	.50	$\frac{3}{4}$
$2\frac{15}{16}$	23.	34.	.70	$\frac{3}{4}$
$3\frac{7}{16}$	31.5	54.	.95	$\frac{7}{8}$
$3\frac{15}{16}$	41.	80.	1.30	1
$4\frac{7}{8}$	62.8	156.	2.00	1
$5\frac{7}{8}$	91.1	270.	4.00	1

The actual horse-power which it is allowable for the shaft to transmit is given in the table at 100 turns per minute: for any other speed the power varies in proportion; that is, at 200 revolutions per minute it would be twice as great.

It is not convenient to make or use shafting in greater lengths than 25 feet for sizes from about $1\frac{7}{16}$ to $3\frac{7}{16}$ inches diameter; for larger or smaller sizes it is desirable to have the lengths still less. It is usually a mistake to try to use greater lengths, as they have to be made specially, and are difficult to transport and put up.

The lengths of shafting are connected by some of the following forms of coupling.

Shaft Couplings. — There are two types of these devices, — rigid and detachable. The ordinary form of rigid coupling is the flange type shown in Fig. 81, which should be secured to the shaft by tapered keys. This is usually preferable to the plain sleeve coupling, which consists of a tube in which the ends of the shaft are held by set screws or keys, for the reason that the former allows the sections of shaft to be more easily disconnected or removed.

Fig. 81. Flange Coupling.

The clamp or compression couplings, of which there are many forms, simply grip the shafts by screw pressure. They possess the advantages of being easily put on or taken off, and do not require holes or slots to be cut in the shaft.

The simplest form of detachable coupling is the jaw or "grab" clutch, represented in Fig. 82. This consists of a jaw which slides lengthwise on one of the shafts, and is caused to revolve with it by a feather and slot; this engages with a similar jaw rigidly attached to the other shaft. This clutch enables shafts to be easily connected or disconnected while standing still, or even to be thrown out of gear while in motion; but it is obviously too sudden in its action to be used for connecting a shaft to one already running. For this latter purpose some form of friction clutch is very convenient in connection with the driving of dynamos.

Friction clutches are made in many different styles, the usual arrangements consisting of an inner ring which is expanded

against an outer ring; a rim which is grasped by jaws; or two cones which are forced together. The force is obtained by screws or toggle joints. Fig. 83 shows one type in which jaws carried by the shaft are caused to grasp a rim cast upon the pulley, the latter being mounted to turn freely upon the shaft when the clutch is released. The outer jaw on one side is carried by the

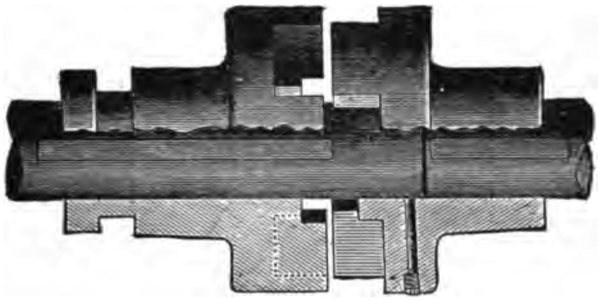

Fig. 82. Jaw Clutch.

same arm as the inner jaw on the other side; hence the grip is obtained by moving one arm upward and the other downward by means of the toggle that is operated by the collar on the left, which, in turn, is caused to slide on the shaft by a fork and lever controlled by hand. If the device is used as a simple friction clutch to connect two shafts, no pulley is required, and the rim is rigidly mounted upon one shaft, and the jaws upon the other. The jaws are shod with maple, which is easily renewable, and their position is adjusted by slightly shifting the wedges against which the short end of the main lever acts, the wedges being set by means of nuts, as shown. These clutches are made with two, four, or six arms, according to the amount of power to be transmitted.

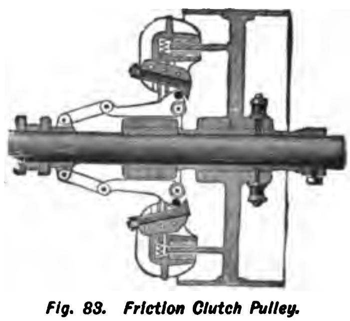

Fig. 83. Friction Clutch Pulley.

Magnetic Clutches. — The substitution of magnetic attraction for ordinary mechanical force, to obtain the friction required in a clutch, secures several decided advantages. The most important of these is the fact that the pressure is *self-contained*, the attraction being exerted only between the friction surfaces, without any

of the end thrust or external force involved in all mechanical clutches. Furthermore, the complication of levers and pivots is avoided, the parts being few and simple. The chief difficulty lies in the arrangement of the electric circuit and connections; but in an electric plant where current is available and electrical apparatus is understood, this objection becomes insignificant. Magnetic clutches have not been used to any great extent; but this is simply because they have not been taken up by engineers and manufacturers, and worked out in detail for various sizes suited to commercial requirements. Fig. 84 indicates a form of mag-

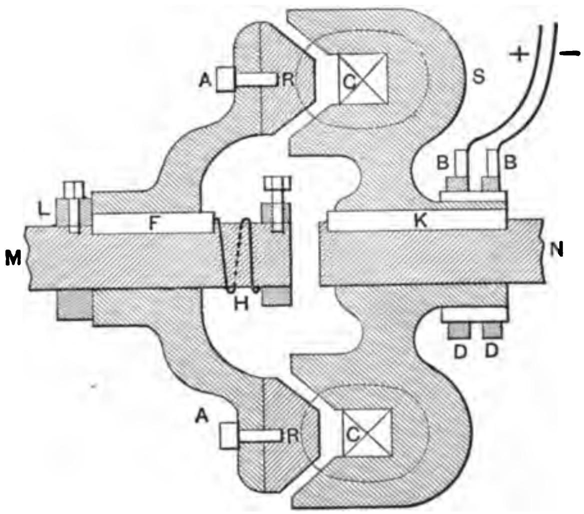

Fig. 84. Magnetic Clutch.

netic clutch which consists of an annular magnet *SS* of cast-iron or steel mounted upon the shaft *N*, and rigidly held by a key *K*. *CC* is a magnetizing coil, the terminals of which lead respectively to the two insulated rings *DD* mounted upon the hub of *SS*. The stationary brushes *BB* bear upon these rings, and connect the coil with the supply of current by the wires marked + and −. When the current is caused to flow through the coil *CC*, the magnet is energized, and attracts the cast-iron ring *RR*, forcing the conical surfaces together, the path of the lines of force being indicated by dotted ovals. The ring *R* is bolted to the support *AA*, which is mounted upon the shaft *M*, and is capable of a slight

longitudinal movement, but is prevented from turning upon the shaft by a feather *F*. The spring *H* throws the support *A* back against the collar *L*, so that the ring *R* is out of contact with the magnet when the current is stopped. If the magnet *S*, or its wearing surface, is made of cast steel, and the ring *R* is of cast iron, most of the wear will be confined to the latter, which may be easily and cheaply renewed.

The grip obtained by such a clutch is enormous; since the magnetic attraction is readily made 50 to 100 lbs. per square inch, the effect of which is increased by the wedging action of the conical surfaces. A magnetic clutch can be controlled at any desired points or from any reasonable distance; and two small wires suffice to carry the current required, since the magnetic circuit is very short and completely closed. The thrust of the spring *H* is insignificant, since it need only be sufficient to throw the ring *R* back when the magnetic attraction ceases.

Clutches very similar to the form shown are used in the power station at Fort Dodge, Io., to control two 750 kilowatt dynamos.*

Hangers and floor-stands are required to support a main or counter-shaft, an ordinary form being shown in Fig. 85. In laying out and putting up a line of shafting, the greatest possible care should be exercised to make the alignment perfect, in order to reduce the friction, strains, and noise to a minimum, since the speed in electrical practice is usually high. The ceiling, floor, or foundations which carry the shaft should be sufficiently rigid, and free from danger of settling. The hanger is adjustable vertically by means of the screws, as shown. The horizontal adjustment is ordinarily made by providing slots for the lag-screws which hold the hanger in place, so that by loosening these screws the entire hanger can be shifted slightly.

Fig 85. Hanger

More substantial forms of hanger are made for large shafts, the frame being a much heavier casting, and the box being adjustable by screws horizontally as well as vertically, so that it is not

* *Western Electrician*, Oct. 12, 1895.

necessary to shift the whole hanger. Almost any form of hanger can be converted into a floor-stand by simply inverting it; but the box should be taken out by loosening the vertical screws, and put back in an upright position, so that the oiling devices will work properly.

Fig. 86. Floor Stand.

For large shafts of about 4 to inches in diameter, still more substantial floor-stands are made in the form represented in Fig. 86. The boxes are adjustable horizontally and vertically by means of screws, as shown.

Pulleys. — The kinds of pulley in general use are cast-iron, steel-rim, and wooden pulleys. The common cast-iron pulleys are simple, cheap, and can readily be obtained, sizes up to 8 or 10 feet in diameter being regularly

Fig. 87. Steel-Rim Pulley.

made by the manufacturers, and special sizes can be cast in any foundry. They can be had either solid, split, clamp-hub, flange, or loose pulleys. The ordinary solid form requires to be bored to fit the shaft exactly, as the slightest looseness will cause it

to run "out of true," hence difficult to put on or take off. Split pulleys are easily mounted upon or removed from the shaft without interfering with the hangers or other pulleys, and can be made to fit on the shaft tightly. A pulley with a clamp-hub is split through the hub only, the rim being solid. The slight elasticity thus obtained allows for small differences in diameter, and enables the pulley to be clamped very firmly on the shaft.

Pulleys are often made with one or two flanges, to prevent the belt from running off, and might be desirable, for example, where machinery was subjected to momentary overload, which would throw off the belt. Tight and loose pulleys are used to connect and disconnect machines by shifting the belt from one to the other; but for driving dynamos, and for other heavy work, it is now customary to use friction clutches (Fig. 83), which occupy less space.

Steel-rim pulleys are light, strong, and neat in appearance. They consist of a steel rim screwed or riveted to arms or to a web of cast iron. The latter form is shown in Fig. 87, and is adapted to high speeds, since the web is stronger, neater looking, can be more perfectly balanced, and would have less air resistance than a pulley with arms. In fact, it is often better to make any pulley up to two feet or more in diameter with a web, and gain the four advantages stated, as there is practically no disadvantage. This applies also to a simple cast-iron pulley, which can be turned in a lathe almost perfectly true if made with a web. We have seen, in the case of large fly-wheels (page 143), that the peculiar strains and danger of bursting are chiefly due to the effect of the arms, and are practically avoided by the use of a web.

Wooden pulleys are very light, smooth-running, easily put on or taken off, give a better hold to the belt, and, since they are usually clamped on the shaft, they do not require any set-screw holes or key-ways to be made in it.

The lightness of a wooden pulley facilitates the handling and mounting of it, reduces the weight on the shaft and hangers, and if the pulley is not perfectly true the objectionable effects are much less. A typical form of wooden pulley is shown in Fig. 88. The two halves are bolted together on the pulley, a wooden bushing being interposed as represented. Bushings are made of various sizes to fit the different diameters of shaft.

Smaller wooden pulleys are made without arms, two solid semicircular blocks of wood being bolted together. Wooden pulleys,

Fig. 88. Wooden Pulley.

even including the smallest sizes, are usually built up of several sections of wood, as indicated, in order to give strength and avoid warping; but forms of pulley are also made which consist of a bent hard-wood rim, cast-iron hub, and wooden spokes.

CHAPTER XVI.

TOOTHED, FRICTION, AND OTHER GEARING.

Toothed gearing possesses the decided advantages of positive action and the ability to give large ratios of speed, which, in the case of driving dynamos, are often required. This form of connection also has less side pressure than belting and friction gearing. Nevertheless, gearing is rarely used for driving dynamos, except in connection with turbines having vertical shafts; and even then its desirability is questionable, since it usually requires belting also, the turbine being geared with a horizontal shaft which is belted to the dynamo. The complication and indirectness thus involved are so great that either a turbine with a horizontal shaft, or the plan of mounting the dynamo directly upon the upper end of a vertical shaft, as is done at Niagara, is generally preferable.

It is difficult to explain why ordinary spur-gearing is not more often used, instead of belting, to connect a steam-engine and dynamo. A large ratio of speed could be easily obtained, and the space occupied would be far less; in fact, the compactness of this arrangement would be almost equal to that of direct coupling. The noise occasioned by gearing is one reason why it is not used; but it is employed almost universally for electric cars, where the noise is more objectionable, and the conditions much more severe, than in electrical generating-plants. All that is required to make gearing work well is perfectly cut teeth and reasonable speeds, both of which can be easily realized; indeed, the latter condition is not essential, since the Laval steam-turbine, which runs at ten or twenty thousand revolutions per minute, is connected to the dynamo by means of spiral gearing (page 181). It would therefore appear that gearing is perfectly available as a means of connecting engines or other prime movers with dynamos.

The theory and practice of gearing form a special subject, the treatment of which may be found in the works referred to at the

end of the present chapter; but ordinarily the electrical engineer can obtain perfectly cut gear-wheels of any desired size from some reliable manufacturer, such as Brown & Sharp, and it would usually be a foolish waste of time and money to attempt to design or make them. However, a certain knowledge of the principles of gearing is desirable.

There are two kinds of gearing, *epicycloidal* and *involute*, depending upon the form of the teeth. The former is more perfect in its action, but the latter is not so much affected by wear or by a slight variation in the distance between the two shafts. The object of both forms of gearing is to obtain a *rolling* action of the teeth, and the minimum amount of sliding; nevertheless, a certain amount of the latter always occurs.

The pitch diameters of gear-wheels are their effective diameters, and determine the ratio of speeds. The *pitch circle*, which is described on the pitch diameter, is usually about midway between the tops and bottoms of the teeth; but the latter might be cut deeper, or extended outward, without necessarily affecting the pitch circle. The size of the teeth is given either in *circular pitch* or *diametral pitch;* the former being the distance in inche from the center of one tooth to the center of the next, measured on the pitch circle. Diametral pitch, which is more often considered, is the total number of teeth divided by the pitch diameter. *Obliquity* in gearing is the angle between a tangent to the surfaces of contact of the teeth and a line joining the centers of the two wheels. Theoretically, the acting-surfaces of the teeth should be exactly on the line between the centers; but practically, in involute teeth the obliquity either varies between 0° and about 30° during the approach and recess of the teeth, or it is constant at about 14½°. The obliquity tends to force the wheels apart, and exerts a side pressure on the bearings of both wheels. The minimum number of teeth which it is desirable for a *pinion* or small gear-wheel to have is twelve, for the reason that the obliquity becomes too great with a lesser number, or the teeth have to be undercut and weakened at the bottom. In fact, noise, wear, and inefficiency are all greatly increased by attempting to use very small pinions. It is much better for the smallest wheel to have at least 16 teeth, and 20 or 24 would be preferable. All that is involved is a corresponding increase in the size of the

other wheel, which is usually allowable. Where space is very limited, as in the case of an electric car, it may be absolutely necessary to make the size of the pinion a minimum, in order to secure the required reduction in speed; but for driving dynamos in stations or elsewhere, there is almost always sufficient space for larger gear-wheels.

The strength of gearing depends upon the size and shape of the teeth, each of which may be considered as a cantilever or beam firmly fixed at one end and loaded at the other. If P is the total pressure exerted on the outer edge of a tooth, h the height, b the width of face, and t the thickness of the tooth, f being the greatest safe stress, which is from 3,000 to 6,000 lbs. per square inch for cast iron depending upon the speed, liability to shock, etc., we have: —

$$P = \frac{bt^2f}{6h}.$$

It is often assumed that two pairs of teeth are always in action, so that each carries only one-half of the total pressure; but it is doubtful if it is wise to count on this, since a slight shifting of position, or the presence of dirt, might throw the whole strain on one tooth. In fact, the pressure might all be exerted at one corner of a tooth, in which case the strength of its entire width is not available. This, however, is covered in any ordinary case by the factor of safety assumed above. In discussing the minimum number of teeth allowable in gearing, it might have been thought that a smaller pinion could be made by having a number of teeth greater than twelve but smaller in size; but it is now clear that the size of each tooth must be sufficient to transmit the entire pressure. Moreover, this force increases as the diameter of the wheel is decreased, the power and speed being constant; so that it would require a still larger tooth. This is an additional reason for not using very small pinions.

The modern tendency is to shorten the teeth of gear-wheels, and make their total height only about .5 instead of .6 or .7 of the pitch. The strength thus gained enables a greater number of smaller teeth to be used, which increases the steadiness of action, and makes it possible to run gearing at high speeds without excessive noise, wear, or lost power.

A gear-wheel must be capable of withstanding the effects of centrifugal force, as in the case of fly-wheels, which were fully discussed in Chapter X. The peripheral speed of gearing for driving dynamos would rarely exceed 50 feet per second, however, which is only one-half the speed allowed for cast-iron fly-wheels. This lower speed-limit, producing only one-quarter as great centrifugal force, would make up for the fact that the teeth add to the weight, but not to the strength, of gear-wheels, the expression for calculating the strength of such a rim being given on page 142. The ordinary material for gear-wheels is cast iron; but steel should be used for any wheel which is considerably smaller than the other, the wear on each tooth being correspondingly increased. Rawhide or wooden teeth are sometimes used to deaden the sound.

The Arrangement of Gearing. As already stated, gearing is seldom used for driving dynamos, except where the source of power is a turbine with a vertical shaft, in which case the power may be transmitted to a horizontal shaft by means of bevel-gearing. This horizontal shaft might be that of the dynamo itself, but usually it is a line-shaft to which a number of dynamos are connected by belting. The latter method is indirect, but may be necessary where several dynamos are to be driven by one turbine, as in series arc-lighting.

Gearing is also employed to connect windmills with dynamos, in order to obtain the required multiplication of speed, and also to transmit the motion of the windmill shaft to the dynamo below by means of a vertical shaft and bevel-gears. But the dynamo being usually small, it might be placed in the top of the tower, near the shaft of the mill, and connected to it by belting.

FRICTION-GEARING.

One of the simplest means of driving a dynamo is to cause its pulley to press against the fly-wheel of the engine or other prime mover, thus obtaining what is known as friction-gearing. This has the advantages of simplicity, compactness, it can be designed for any reasonable ratio of speeds, and is instantly thrown out of gear by merely moving the dynamo a small fraction of an inch on its sliding base. In all these respects nothing could be more desirable; but friction-gearing has not been very exten-

sively or successfully applied to driving dynamos, or to any other purpose requiring considerable power. The chief objections to its use have been the small amount of power transmitted compared with the side pressure on the bearings, and the fact that considerable vibration is likely to occur, owing to the wheels being rigidly in contact, with no elasticity or opportunity for play; hence the slightest irregularity on either wheel would cause both machines to vibrate. This difficulty is aggravated by the wear which occurs at one point of a wheel when the other wheel slips, as is sure to occur occasionally in starting or from overload. This makes it practically impossible to keep the wheels perfectly true.

The common idea is that it is not practicable to obtain sufficient driving-force with friction-gearing; but when it is remembered that locomotives secure enormous tractive force by the mere friction of the driving-wheels upon the rails, it would seem that this objection is not valid. When the wheels of a locomotive slip on the track they tend to wear away the track at that point, but the very great length of the track distributes the wear; whereas in friction-gearing one of the wheels would be made imperfect at that spot. It should be noted that it is not the wheel which slips that is made untrue; it is the other surface.

One form of friction-gearing consists of wooden wheels with V-shaped grooves in their peripheries which fit together. By this construction a wedging-action is obtained which increases the friction and gives a greater tangential pull, with a given side-pressure on the bearings, as in the case of rope-belting in grooved wheels. But in friction-gearing of this kind the velocities of the two wheels do not agree at the top and bottom of the grooves, consequently there is considerable wear and loss of power by the fact that there is a sliding as well as rolling action.

This difficulty is overcome by the use of simple cylindrical wheels of wood or cast iron. These may be covered with leather to increase the friction and reduce the vibration and noise, which latter would be quite objectionable if plain cast-iron wheels were used. The trouble with this form of friction-gearing is the wear which occurs when the wheels slip, as already explained. The horse-power transmitted by friction-gearing is, $H.P. = \frac{\pi DAPS}{33000}$, in which D is the diameter in feet, and S the speed in revolutions

per minute of either wheel, A is the coefficient of friction, and P is the normal pressure in pounds with which the wheels are held together.

Evans's Friction-Gearing. — This is a special form which has been quite extensively used for driving dynamos and other purposes. It consists simply of an endless leather belt which fits loosely on one of the two pulleys between which the power is transmitted. The belt is held in place by flanges on both sides of the pulley which it surrounds. When the two pulleys are pressed together this belt is interposed between them, and acts to secure the frictional grip, as well as to deaden the vibration and noise. In fact, this arrangement simply amounts to cast-iron friction-wheels, one of which is provided with a leather covering that is free to revolve or stop independently of the wheel. This allows the belt to adjust itself, or slip, and reduces the danger of its being torn or worn badly in case of overload.

The principles of the Evans friction-gearing, and a comparison with ordinary belting, is given in an article by H. T. Conant.* It is claimed in this article, and also by the manufacturers, that the coefficient of friction is increased because the belt is twisted between the pulleys by the power transmitted, its two surfaces being forced in opposite directions. It is somewhat doubtful, however, whether the tangential pull due to friction is anything more than the normal pressure which must be carried by the bearings, multiplied by the coefficient of friction between leather and iron. But an interesting point in this connection is the apparent thickening of the belt due to this twisting action, it being found in practice that a very slight pressure between the pulleys which is only sufficient to carry a light load is also able to transmit the full power when applied. Thus the virtual thickness of the belt, and hence the pressure on the bearings, automatically adjusts itself in proportion to the load. This is quite an important feature where dynamos are to be driven for long periods of time at light load. With ordinary belting the total pull on the bearings is nearly constant, the effect of the load being to increase the pull on one side, and reduce it on the other.

A special form of the Evans friction-gearing consists of two conical pulleys which taper in opposite directions, the loose belt

* *Electrical Engineer*, March 25, 1891.

being placed on one of them, and being in this case a little larger in diameter than the base of the cone. If one of these cones is fixed to the engine or counter-shaft, and the other is connected directly or by belting to the dynamo-shaft, then any desired ratio in speed may be obtained by simply moving the belt back and forth by means of an ordinary belt-shifter. This is one of the best possible ways to secure a variation in speed which can be gradually and perfectly adjusted, but it is hardly applicable to very large amounts of power.

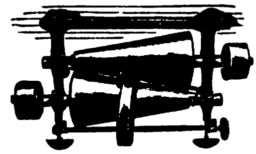

Fig. 89.
Evans Friction Gearing.

Hydraulic gearing has been tried for connecting the motors and axles of electric street-cars, the object being to obtain a variable ratio in speed which is so desirable in that case. One form of this device is described by its inventor, F. M. Barney.*

In general principle hydraulic gearing usually consists of a pump operated by the driving-axle, and feeding a water-engine connected to the driven axle. The device is thrown into and out of gear, and the speed varied by controlling the flow of water by means of valves. The objections to most forms of hydraulic gearing are their complication and the loss of energy which occurs when the speed of the driven shaft is reduced. At half-speed, for example, with full torque, the power lost and the efficiency would each be 50 per cent, since one-half of the water pumped is "short-circuited," or allowed to flow idly past the water-engine, and becomes heated to an objectionable degree, since it is used over and over again. It has been attempted to avoid this fatal difficulty by varying the length of stroke of the pump. This is almost ideal in theory, but as yet no form of hydraulic gearing is in general use. Nevertheless, it may prove to be the best connection for variable speed, with smooth, perfect control and positive action, this combination of results being often extremely desirable in mechanical and electrical engineering.

Magnetic gearing is another undeveloped but promising means of mechanical connection. A simple form of it consists of two iron wheels, one of which carries a coil of wire in one or more grooves cut in its periphery. An electric current sent through the wire magnetizes the wheel, and causes it to attract the other

* *Electrical Review* (N.Y.), May 7, 1892.

with considerable force, so that the two wheels can be used as a sort of friction-gearing.

There is one essential advantage of magnetic gearing, and that is the fact that the pressure which produces the friction is *self-contained*, the two wheels being drawn together by magnetic attraction; whereas ordinary friction-gearing requires a side pressure on the bearings which is two to five times greater than the frictional grip obtained. A pair of magnetic gear-wheels each about 6 inches in diameter, constructed by the author, transmitted about one horse-power at a speed of 1,500 revolutions per minute. This was an excellent result for such small wheels; and their action was in every way satisfactory, except that they made a loud humming noise that was decidedly objectionable. Unfortunately, the interposition of leather to deaden the sound would greatly reduce the magnetic attraction. It is desirable that the wheels should be laminated, or built up of iron disks, to prevent the generation of Foucault currents. The electrical energy required to magnetize the wheels is small, since the magnetic circuit is closed, only about ten watts being used in the experiment cited.

Further information in regard to belting, gearing, and other means of connecting engines and dynamos, may be found in the following books and articles: —

Machinery and Millwork, by W. J. M. Rankine, Sixth Edition, London, 1887.

Elements of Machine Design, by W. C. Unwin, London, 1891.

Treatise on the Use of Belting, by John H. Cooper, Philadelphia, 1895.

Belt Driving, by George Halliday, New York, 1894.

A Treatise on Belts and Pulleys, by J. H. Cromwell, New York, 1894.

A long series of articles on "Rope Driving," by J. J. Flather in the *Electrical World*, N.Y., beginning Oct. 21, 1893.

Gear Tables, by Prof. J. F. Klein.

A Treatise on Gear Wheels, by George B. Grant, Lexington, Mass., 1893.

Formulas in Gearing, Brown & Sharpe Mfg. Co., Providence, R.I., 1892.

A Treatise on Toothed Gearing, by J. H. Cromwell, New York, 1894.

CHAPTER XVII.

PRINCIPLES AND CONSTRUCTION OF DYNAMOS.

Introduction. — The history of these machines has already been given in the general history of electric lighting contained in Chapter II., since to a great extent the history of electric lighting is the history of the dynamo.

A dynamo is a machine for converting mechanical energy into electrical energy by causing conductors to move in a magnetic field, or *vice versa.* These machines operate according to the principle of magneto-electric induction discovered by Faraday in 1831.

The problem of constructing a dynamo consists of three parts. First, the production of a strong magnetic field by means of a suitable electro-magnet; second, the design of an armature adapted to revolve in the magnetic field, and carrying the conductors in which the electric current is generated; and third, the mechanical construction and arrangement of the various parts so that the action of the machine may be as effective and reliable as possible. The understanding of the dynamo, therefore, requires a knowledge of three great branches of science, — magnetism, electricity, and mechanics. Hence it is obvious that it is a subject of considerable difficulty, and can only be thoroughly learned by careful study, based upon considerable previous training. Nevertheless, the dynamo is not a complicated machine, since it consists of very few parts, only one of which moves, being in this respect as simple as it is possible for any machine to be. For this reason almost any one may acquire a sufficient knowledge of the dynamo to operate it successfully. No one should ever attempt, however, to design a dynamo without a thorough knowledge of the magnetic, electrical, and mechanical principles involved, and also considerable practical experience with electrical and other kinds of machinery. Books and papers on the dynamo almost always treat it from the point of view of theory and construction, as if the intention were to make every one a *designer* of dynamos;

whereas the important subject of *managing* dynamos is almost neglected. As a matter of fact, there are fully a hundred times as many persons interested in the use of dynamos as in the designing of these machines. This is particularly true in electric lighting, where it would almost always be a mistake for the engineer to design or build his own machine, even though he were perfectly qualified to do so. But of course the more the engineer knows of the theory and construction of dynamos, the better he can plan and operate an electric-lighting plant; and a considerable knowledge of this kind is absolutely essential. Hence the general principles and constructions of dynamos will first be treated, after which their practical management will be considered.

Parts of Dynamos. — The chief parts of a dynamo are the *armature* and the *field-magnet.* The latter is usually stationary, and is combined with the base and bearings to form what is called the *frame* of the machine. In direct-current machines it is necessary to provide the armature with a *commutator*, which rectifies the current; that is, converts the alternating currents generated in the armature conductors into direct currents. In the case of alternating-current dynamos, simple *collecting-rings* are used instead of the commutator. In either case *brushes* are required to take off the current from the revolving commutator or collecting-rings. In some types of alternator the armature is stationary, and the field-magnet revolves; hence the field-current must be supplied to the moving magnet by a similar pair of brushes and rings. The complete dynamo comprises also the shaft, bearings, and other mechanical details.

Magnetic Field. — If an ordinary permanent magnet be laid upon a table, and approached by a compass-needle, or by a small piece of iron or steel suspended by a thread, the latter will be attracted by the magnet, and tend to point towards it. The space near the magnet in which these phenomena take place is appropriately called the *magnetic field*, or simply the "field." This region has no definite limits, since the distance at which magnetic effects can be obtained simply depends upon the sensitiveness of the instrument used. Delicate galvanometer needles, for example, may be deflected very perceptibly at a distance of several hundred feet from the field-magnet of a large dynamo. It is customary, however, to consider the magnetic field as being confined to the

immediate neighborhood of the magnet where the effect is strong, the latter being usually made in a form to concentrate the field as much as possible. The extremities of a magnet usually exhibit magnetic properties much more strongly than the middle portions, and are therefore called the *poles*. The usual way to consider magnetism is to look upon it as consisting of a number of "lines of force" or "tubes of force." This conception is suggested by the lines in which iron filings arrange themselves under the influence of a magnet; and the direction and intensity of the field are represented by the direction and number of the lines. This idea is often very convenient, but it should not be taken too literally, as it sometimes leads to wrong notions.

The Magnetic Circuit. — In order to localize and strengthen the magnetic field, and to economize the wire and current required to produce it, the magnets of dynamos and other electromagnetic apparatus are arranged in such a form that the path of the lines form a closed circuit; that is, they are carried for the most part in the iron, only a sufficient *air-gap* being left for the electrical conductors and the clearance which they require for free motion. In Fig. 90 the general form of the magnetic circuit of a dynamo is shown, *CC* being the *magnet cores*, upon which are wound or placed the *coils* or *bobbins* of copper wire *BB* through which the exciting current flows. *Y* is the *yoke* which connects the two cores, and forms with them the "horseshoe" type of magnet. The extremities of the magnet are provided with *pole-pieces PP*, which are bored out or shaped to receive the armature, which consists of the *armature core a* and *armature conductors* or "winding" *W*.

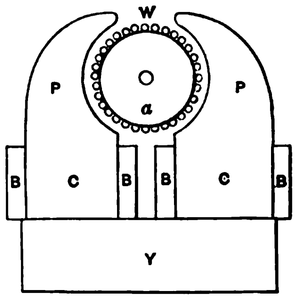

Fig. 90. Magnetic Circuit of Simple Dynamo.

Various other forms of magnet are used in practice, but in almost every case they are really equivalent to the horseshoe form shown; and even in the case of the *multipolar* field-magnets, that is, those having more than two poles, it is usually possible to consider them as being made up of several horse-shoe magnets, or, in other words, two or more magnetic circuits. Dynamos and

other machines are sometimes made with simple bar-magnets, in which the magnetic circuit is apparently incomplete. As a matter of fact, however, even in this case each line of force passing through the magnet is completed through the air; but it is evident that in such arrangements the magnetic resistance or reluctance is far greater than if the circuit were almost entirely composed of iron, since the reluctance of air is several hundred times that of iron under ordinary conditions.

Calculations in regard to the magnetic circuit are usually made by means of a formula analogous to Ohm's law for the electric circuit, this expression being: —

$$\text{Flux} = \frac{\text{Magnetomotive force}}{\text{Reluctance}}$$

There is, however, one important difference between this formula and Ohm's law; this being the fact that the reluctance is not a constant or an independent quantity like electrical resistance. Reluctance depends upon the value of the flux, or rather upon the magnetic intensity: hence it is necessary to know the number of lines of force per square centimeter in the iron, in order to fix the value of the reluctance; whereas electrical resistance has a constant value, and is entirely independent of the strength of current, provided the temperature does not change. This difference between resistance and reluctance makes magnetic calculations more difficult than the corresponding electrical ones. Another difficulty is the fact that magnetic leakage is usually a much larger factor, and more difficult to determine, than electrical leakage. Nevertheless, calculations of magnetic quantities can be made with reasonable accuracy, the ordinary error not being more than one to five per cent.

Magnetic Flux. — The total quantity of "induction" or field in a magnetic circuit is called the flux, and is measured in lines of force. The term "line of force" was originally used by Faraday in a general sense to express the direction and intensity of magnetism in something the same way that the expression "ray of light" is used. When, however, magnetism came to be measured definitely, the line of force was adopted as the unit of magnetic field or flux. If we follow the derivation of the value of the line of force, we find that a *unit magnetic field* exists at the distance

of one centimeter from a *unit magnetic pole*, the latter being a pole of such strength that it repels a pole of equal strength with a force of one dyne at a distance of one centimeter. Each square centimeter of the surface of an imaginary sphere with one centimeter radius described about a unit pole will contain a flux of one line of force; and since the total surface of the sphere is 4π, it follows that 4π, or 12.57 lines, emanate from a unit pole. This somewhat abstract and indirect definition may be made much shorter and more convenient for dynamo calculations by simply stating that one hundred million lines of force cut per second generate one volt *E.M.F.* Since the value of the volt and other electrical units has been defined and legalized internationally, it is proper to base the magnetic units directly upon the electrical ones. The ordinary value of the flux, or total number of lines of force in a dynamo machine, is from about 10^6 lines in a machine of 1 horse-power to about 10^8 lines in a machine of 1,000 horse-power. Very frequently, instead of considering the total flux we treat the *flux density*, or intensity of magnetic field; that is, the number of lines of force per square centimeter. This quantity multiplied by the area of the field or cross-section of the magnet gives the total flux. The maximum flux density which is used in practice is from 14,000 to 15,000 lines of force per square centimeter (about 90,000 to 100,000 per square inch) for wrought iron, and from 6,000 to 7,000, or about one-half as much, for cast iron. These values are what are called "practical saturation," beyond which it is not ordinarily worth while to go. As a matter of fact, however, Ewing and other experimenters have forced magnetic density as high as 43,000 lines of force per square centimeter. On the other hand, in alternating-current transformers the ordinary flux density has a maximum value of only about 5,000 or 6,000 lines, in order that the loss due to hysteresis shall not be excessive.

Magnetomotive Force. — This depends directly upon the *ampere turns*; that is, upon the product of the number of turns of wire, and the number of amperes flowing through them — in fact, *M.M.F.* is often given in terms of the ampere turns simply; but, strictly speaking, the *C.G.S.* value of *M.M.F.* is 1.257 times the ampere turns. This is because the difference of magnetic potential on opposite sides of a turn of wire is equal to 4π times

the current flowing in the wire; and since the ampere is one-tenth of the absolute unit of current, it follows that the ampere turns must be multiplied by $\frac{4\pi}{10}$, or 1.257, to obtain the *C.G.S.* value of the magnetomotive force. The magnetic circuits of dynamos usually have from 3,000 to 10,000 ampere turns, depending upon the length of the circuit, the air-gaps between the pole-pieces and the armature core, and the material of, and magnetic density in, the field-magnet and armature.

Magnetic Reluctance. — The unit of this quantity is the reluctance of one cubic centimeter of space, i.e., vacuum; and since almost all substances except iron have practically the same magnetic reluctance as a vacuum, it follows that one cubic centimeter of any of these substances has practically one unit of reluctance. This is true of air, copper, brass, wood, paper, cotton, silk, mica, porcelain, or almost any material except iron that is likely to form part of the magnetic circuit. This fact, of course, tends to simplify magnetic calculations. The reluctivity of wrought iron varies from about .00033 at a flux density of 4000 to .0031 at 16,000 lines of force per square centimeter. Other metals besides iron, notably nickel and cobalt, have a reluctivity considerably less than unity; but they are so vastly inferior to iron as magnetic conductors, that they are very rarely employed. It is also customary to consider the *permeability* of iron and other substances, this being the reciprocal of the reluctivity.

Fig. 91 gives the magnetization, or "*H-B*" curves, for wrought and cast iron and mild steel, and shows the relation between *B*, the induction or flux density in lines of force per square centimeter, and *H*, the magnetizing force, or *M.M.F.* in *C.G.S.* units, which are equal to the ampere turns multiplied by 1.257, as already explained. The flux per square inch is 6.45 times the flux per square centimeter. These curves are taken from a paper by Milton E. Thompson and others on "The Magnetic Permeability of Special Irons for Electrical Purposes." *

Magnetic Hysteresis. — When the direction or density of magnetic flux in a piece of iron is changed, a certain loss of energy occurs. This is due to the fact that the value of the flux lags behind, and does not correspond exactly with variations in the

* *Trans. Amer. Inst. Elec. Eng.*, vol. ix., p. 250, 1892.

M.M.F. This phenomenon is shown in magnetization curves. In Fig. 91, for example, the value of B would be less in each case for a given value of H when the latter is increasing than when it is decreasing. According to Steinmetz,* the loss due to

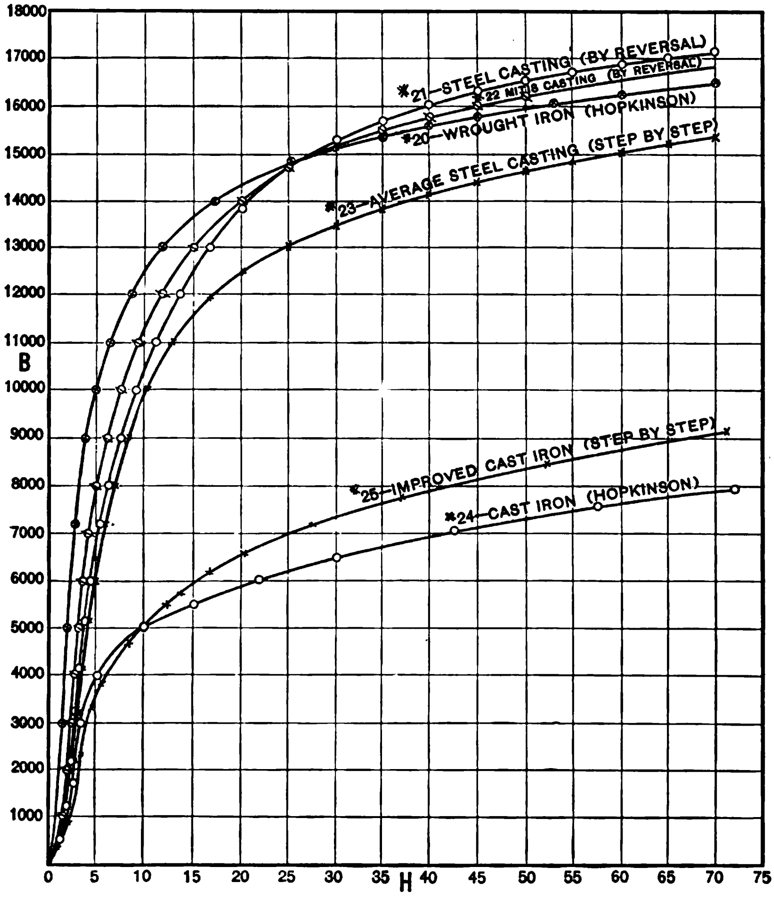

Fig. 91. Magnetization Curves for Iron and Steel.

hysteresis is represented by the empirical formula: $H = \eta B^{1.6}$, in which H is the lost energy in ergs per cycle and per cubic centimeter, B is the maximum value of the induction or flux density, and η is a coefficient depending upon the physical and

* "On the Law of Hysteresis," *Trans. Amer. Inst. Elec. Eng.*, vol. ix., pp. 3 and 621.

chemical qualities of the material. For armature and transformer cores, only the best and softest sheet iron or mild steel should be used, the value of η for this material being about .002 to .003. In most field-magnets the flux density is practically constant, hence hysteresis need not be considered. Calculations of the hysteretic loss in armature cores usually give results higher than those obtained by actual test. This probably arises from the fact that when the direction of the flux is progressively shifted without changing its quantity, the loss of energy by hysteresis is not as great as when the flux is directly reversed as it is in the case of a transformer.*

Generation of E.M.F. — Whenever magnetic lines of force are cut by a conductor, an *E.M.F.* is set up in it, the value of which is one volt when 100,000,000 lines are cut per second; or, in other words, it depends solely upon the *rate* of cutting, so that one volt is also set up if 1,000,000 lines are cut in one-hundredth of a second. In both cases the rate of cutting is supposed to be uniform throughout the given time.

The generation of *E.M.F.* is absolutely certain, no matter when or by what process the lines are cut. A *current*, however, is only produced when there is a closed circuit in which it may flow. A straight bar of copper, for example, cutting across a magnetic field, would have an *E.M.F.* set up in it, and an actual difference of potential would exist between its ends; but there could be no flow of current, except possibly a very slight displacement current at the moment when the *E.M.F.* is established. We should always clearly distinguish, therefore, between the generation of *E.M.F.* and current. It may happen, also, that there may be two or more opposing voltages which neutralize each other, so that there is no current, even though the circuit is apparently closed. For example, when a copper ring is moved across a uniform field, the two halves will cut an equal number of lines, and the *E.M.F.* in one half is exactly equal and opposed to that in the other half of the ring. Consequently, in order to generate an effective voltage and current in the ring, it is necessary that the field should vary in intensity so that one side of the ring shall cut more lines than the other. This explains the fact that the flux

* See note on the "Hysteresis of Iron and Steel in a Rotating Magnetic Field," by F. G. Baily, British Association, 1894.

in a coil of wire must be varied to produce a current, or, in other words, the coil must be filled with, and emptied of, lines of force, in which case an alternating current is generated. This is often stated so broadly, however, that it seems to mean that an *E.M.F.* cannot be obtained in a uniform field. But, as already stated, an *E.M.F.* *must* be produced whenever magnetic lines are cut.

DYNAMO CONSTRUCTION.

In considering the materials and proportions of the various parts of dynamos, the construction of the armature is taken up first, since it is the portion in which the current is generated, and usually its type and size are determined or approximated in the first place, the field-magnet, base, and other parts being made to conform to the armature.

Forms of Armature. — Any electrical conductor, as, for example, a simple coil of wire revolving or moving in a magnetic field, would act as an armature, and would tend to have an electromotive force set up in it. In order, however, to obtain the maximum effect with a given amount of material, and to secure compactness, convenience of working, and other practical conditions, the armature is usually made in one of two forms, — the *ring armature*, and the cylinder, or *drum armature*. In the former type the copper conductors are wound or placed upon an iron core of ring form, the conductors being carried through the interior of the ring, as well as around the outside. In the drum type the conductors are located wholly on the surface or ends of a cylindrical iron core. In both cases the function of the iron core is twofold: first, it bridges across between the pole-pieces, and greatly reduces the reluctance of the magnetic circuit; and, second, it affords a solid support to carry the electrical conductors. Two other forms of armature are sometimes employed. One of these is the *pole armature*, in which conductors are wound around radial iron cores projecting outward from a central hub; and the other is the *disk armature*, in which the conductors are arranged in the form of a flat disk, the plane of which is perpendicular to the shaft. This last style of armature is the only one which does not require an iron core, since it rotates in a narrow space between the pole-pieces.

Armature Cores. — Originally the core was made of one solid piece of iron; but this permits currents to be set up in it, since the outer portions of the core cut practically as many lines of force as the armature conductors themselves. These useless currents, which are called Foucault or eddy currents, consume a large amount of energy, and also cause excessive heating. Hence it is necessary to subdivide or *laminate* the core, to prevent these wasteful currents from flowing. The usual plan is to build up the core of disks, or rings of sheet iron insulated from one another, so that the magnetic lines can pass freely through each disk; but the Foucault currents, which tend to flow perpendicular to the disks, are stopped by the insulation between the latter. Hence the core should always be laminated parallel to the lines of force, and to the direction of motion. For example, a flat-ring armature, with the pole-pieces on each side, and the lines of force passing perpendicularly through it, should be made of concentric hoops, or, more conveniently, of a roll of iron ribbon.

Iron wire has been employed for armature cores, and possesses the advantages of very perfect subdivision, and of being easily wound in a core of any desired size and form. It has, however, the disadvantages of magnetic discontinuity, and considerable loss of space between the wires if they be of circular cross-section.

Disks or rings are used almost exclusively for armature cores, and are punched out of the softest sheet iron or mild steel, from .015 to .025 inch thick. In armatures of ordinary size each disk is a complete circle in one piece, but ring armatures of large diameter are built up of a number of segments. The laminæ are insulated from each other by tissue paper, paint, varnish, or simply by rust on the surface of the plates. Ordinarily, rust on both surfaces, and paper at every third or fifth plate, are sufficient. This usually brings the loss from Foucault currents down to about one per cent. It is hardly worth while to attempt further reduction, since the trouble of punching and handling many sheets of very thin iron, and the loss of space between the plates, more than offset the gain. On the other hand, a Foucault loss greater than two per cent perceptibly lowers the efficiency, and produces excessive heating in the core.

Toothed Armatures. — The core is often provided with projecting teeth, between which the conductors are laid. This form,

which is also called the Pacinnotti armature, after its inventor, has the following advantages over the smooth core: —

1. The reluctance of the air-gap is reduced to a minimum.
2. The armature conductors are protected from injury.
3. The conductors are firmly held in place, and cannot slip on the core by the action of the electrodynamic force exerted upon them, which in a smooth core is equal to the total torque.
4. Eddy currents in the armature conductors are avoided, since the lines snap across the latter instantly.*
5. If the teeth are practically saturated by the field-magnetism, they oppose the shifting of the lines by armature reaction (which will be considered later).

The disadvantages of a toothed armature core are: —

1. It is more expensive to make.
2. The teeth tend to generate eddy currents in the pole-pieces.

This last difficulty can be practically overcome by making the distance between the teeth less than 2½ to 3 times the air-gap, so that the lines can spread from the corners of the teeth, and become nearly uniform on the pole-faces. If the slots are wider than this, the pole-pieces should be laminated or grooved in the direction of the motion of the armature, or the entire armature may be covered with a layer of iron wire, producing a continuous magnetic surface. This layer should be thin enough, however, to avoid any considerable magnetic leakage through it.

Hystersis in Armature Cores. — This should be reduced to a minimum by the use of the best and softest sheet iron or mild steel; and since the edges of the disks are considerably hardened by the process of punching, it is well to subsequently anneal them by raising them to a bright red heat, and allowing them to cool very slowly. This also has the effect of burning off the burr from the edges of the disks, and oxidizes their surfaces so that they are partially insulated from each other with respect to the eddy currents which tend to be set up in the armature core. The physical data of hysteresis have already been given on page 270.

Size and Form of the Armature Core. — The core must be large enough to carry the inductors required to generate the necessary *E.M.F.* and current. The cross-section of each inductor

* See a paper on "Magnetism in Its Relation to Induced *E.M.F.* and Current," by Elihu Thompson, *Trans. Amer, Inst. Elec. Eng.*, vol. vi., p. 269, 1889.

is fixed by the current which it must carry, from 600 to 800 circular mils being usually allowed per ampere of current; but the surface of the armature must also be considered, in order that the rise of temperature shall not be excessive. This matter is more fully treated under Heating of Armature, near the end of this chapter. The number of paths through the armature between which the total current is divided should also be known. In bipolar closed-coil windings there are two paths, and each inductor must carry one-half of the total armature current. A four-pole closed-coil winding may be either two or four circuit, as explained under methods of armature winding (p. 284). Therefore, the exact method of winding must be decided upon. The number of armature inductors is determined by the *E.M.F.* to be generated, and is given by the following formula:—

$$S = \frac{60 \times 10^8 \times E}{n \times N},$$

in which S is the total number of inductors counting all around the armature, n is the number of revolutions per minute, and N is the flux in lines of force entering the armature from one pole-piece. This applies to all armatures in which the paths for the current equal the number of poles, but must be modified for the two-circuit multipolar windings, or the double windings described later. The only general rule is the very simple fact that 10^8 lines of force cut per second produce one volt, and the *E.M.F.* generated by one inductor must be multiplied by the number of them in series between the $+$ and $-$ brushes.

Having found the number and size of the inductors, the dimensions of the armature core are determined; but it may be necessary to increase its surface on account of the heating-limit already referred to.

Even for a given *E.M.F.* it is possible to design a short core of large diameter, or a long core of small diameter; and there is usually nothing but judgment or circumstances to decide which is the better. Formerly, drum armatures were made with very long cores of small diameter, the object being to save the "dead wire" at the ends. But this idea is somewhat fallacious, as the turns of wire must inclose a certain magnet flux, and the minimum length of wire would be obtained with a core having a diameter equal to

its length. Similar reasoning applies to ring armatures, which should have a cross-section (on each side) approximately square; but to give sufficient surface, and to avoid excessive diameter, the cross-sections of most cores are made rectangular instead of square. It is undesirable, however, for the length to be great compared with the other dimension. Thus it is evident that there is no direct or royal road to the design of an armature, it being usually necessary, and always desirable, to draw several different modifications in order to compare them and select the best.

Mounting of Armature Cores. — The cores of drum armatures may consist of simple circles of sheet iron having a central hole only large enough to slip on the armature shaft. They are held together either by large nuts screwed directly on the shaft, or by bolts passing through the core from end to end, holes being punched in the disks for the purpose. These bolts must be insulated from the core by tubes and washers of paper, fiber, or mica, otherwise strong currents will circulate through them, involving a serious loss of energy. The disks being very thin, a thicker plate of cast or wrought iron or other metal should be put at each end. The rims of these plates should be beveled quite thin, so that eddy currents shall not be set up in them. Iron end-plates tend to take a certain portion of the flux from the core proper, which, owing to their comparative thickness, produces considerable loss from eddy currents. This may be reduced by interposing between the plate and the core a sheet of thick paper, zinc, or brass, or by making the entire plate of non-magnetic material.

The armature core has the full torque exerted upon it, consequently it must be firmly connected to the shaft in order to be driven positively. One plan to accomplish this is to cut slots in the disks and shaft, in which a key is placed. In other cases the grip secured by clamping the disks tightly together by nuts on the shaft is relied upon to drive the core.

It is somewhat objectionable to have the armature core directly in contact with the shaft on account of eddy currents; but for the most part these tend to be generated in the outer portions of the core, and proper lamination there will prevent them. Nevertheless, it is desirable to insulate the disks from the shaft, to decrease the chance of "grounding" the armature, if for no other reason; hence a tube of fiber or other insulating

material may be put between the disks and the shaft, although this renders it difficult to make and maintain the armature perfectly true and balanced mechanically.

In ring armatures, or even in drum armatures of large diameter, the interior of the core is removed, making it necessary to support the core on some form of spider. This consists of a central hub mounted upon and keyed to the shaft, and provided with radial arms which are bolted or otherwise connected to the armature core. One simple and strong construction comprises two spiders, between the projecting arms of which the core is held by bolts passing completely through both spiders and the core. This requires, however, a certain portion of the core to be cut away by the bolt-holes, and necessitates insulating the bolts from the core and the spiders. These objections are obviated by clamping the disks between flanged spiders which are forced together by nuts on the shafts, no through bolts being used.

The various methods of supporting armatures are very fully described in Thompson's work on Dynamo-Electric Machinery.

Armature shafts are made of machinery steel, and are usually much thicker in the middle than at the ends, as they must be exceedingly stiff to withstand the powerful magnetic side-pull on the core if the latter is even slightly nearer one pole-piece than the other. The shoulders obtained by having the shaft larger in the middle serve to keep the armature in the proper position with respect to the bearings, and also enable nuts to be screwed on the shaft to hold the armature core, spiders, commutator, etc. The torsional strain in armature shafts is often considered, but compared with the transverse strength required it is usually insignificant.

Finishing the Armature Core. — The core should have all sharp or rough edges removed before the conductors are put on. This is done either by filing or turning in a lathe. The latter operation also makes the core perfectly true; but it is very likely to burr over the edges of the disks, thus bringing them into contact, and defeating the object of the lamination. A very fine cut with a sharp, diamond-pointed tool reduces this trouble; but the disks are often taken apart afterward and the burr removed by filing, grinding, annealing, or pickling, which last two processes also oxidize the surfaces, and prevent eddy currents. If the disks

are cut perfectly true in the first place, it is not necessary to turn the core in a lathe.

Armature Insulation. — The core must now be thoroughly insulated. This may be partly accomplished by covering the completed core with one or more coats of Japan or enamel; but this insulation cannot be relied upon to any great extent, since it is very likely to have minute holes or bubbles in it, or be pierced by particles of metal or the rough edges of the disks. Therefore, two or more layers of strong paper, fiber, canvas, or mica, or a combination of these, should always be applied to the core where the conductors are to be laid. A smooth core is entirely covered in this way, but with a toothed core the insulation is usually put in the form of separate troughs in the slots between the teeth. The ends of the core should be insulated with still thicker material, since the strain upon it is greater, particularly at the edges.

ARMATURE WINDINGS.

Armature conductors, or "inductors" as they are called, since the current is produced in them by magneto-electric induction, are almost universally made of copper. The ordinary form consists of simple copper wire, insulated with a double covering of

Fig. 92. Armature with Bar Inductors.

cotton; but rectangular bars of copper, or cables of twisted copper wires, are also used. It is not convenient to handle wire larger than about No. 8 B. & S. (.1285 inch diameter); consequently two or more wires are wound together, or connected in parallel, if a conductor larger than this should be required. Copper bars or cable may be used when the amount of current is sufficient to warrant them. The bars are applied in the form of straight rods, or for ring armatures they may be bent in **U** shape, the end

of one being connected to another, to form a complete winding, by strips of sheet copper, which are riveted into slots cut in the ends of the bars. Fig. 92 shows an armature "wound" with copper bars. Bar inductors are liable to have eddy currents set up in them, because the edge just entering the field generates a higher *E.M.F.* than the other. The resulting loss may be quite serious with wide bars. It is reduced by making the bars narrow tangentially, by sloping the edges of the pole-pieces, so that each bar enters the field gradually, by placing the bars between teeth on the core (see page 275), or by laminating the bars, and twisting them through 180° in the middle. This difficulty, and the means of overcoming it, are fully explained by Hawkins and Wallis.*

Methods of Armature Winding. — The arrangement of the inductors, and the order in which they are connected together to form a complete "winding," constitute one of the most complicated subjects in electrical engineering. This matter is elaborately treated by Parshall and Hobart in a large work entirely devoted to it,† and most of the books on dynamos and motors give considerable space to this subject, notably those by S. P. Thompson, ‡ and Hawkins and Wallis. § A small work by E. Arnold || contains nearly all of the important methods.

Direct and Alternating Current Windings. — In classifying armature windings, the most prominent distinction is between those intended for direct, and those adapted to alternating currents. All armature windings have alternating currents generated in the inductors themselves, which are led out without change if that character of current is desired, but which must be *rectified* and made to flow in one direction only by means of a commutator if a direct current is required. Consequently, a commutator is the distinguishing accompaniment of a direct-current winding. There is no necessary difference between the windings for the two purposes, since a direct-current armature can be made to give an alternating current by connecting two complementary points of the winding to a pair of collecting-rings. In practice, how-

* *The Dynamo*, London, 1893, pp. 245–248.

† *Armature Windings for Electric Machines*, New York, 1895.

‡ *Dynamo Electric Machinery*, London, 1892.

§ *The Dynamo*, London, 1893.

|| *Die Ankerwicklungen der gleichstrom Dynamomaschinen*, Berlin, 1891.

ever, direct-current windings are usually quite different from those designed for alternating currents.

Bipolar and Multipolar Windings. — The form of the magnetic field in which the armature is to revolve largely influences the method of winding the latter. Formerly nearly all dynamos and motors were bipolar, but now machines of 50 kilowatts or more almost always have four or more pole-pieces; and the tendency is to build any machines of over 10 kilowatts capacity with multipolar fields. (English practice is often an exception in this respect, as explained in Chapter XVIII.) Some makers construct even the smallest machines multipolar; but for direct-current work it is doubtful if it is desirable to do so on account of the complication involved.

A Unipolar Winding is, strictly speaking, an impossibility; since all lines of force are *closed loops*, and a "pole" which exists where one or more lines enter an armature must have its counterpart where they pass out. In the so-called Ball unipolar dynamo there are two armatures, each of which is acted upon by one of the poles of bipolar field-magnet, thus apparently justifying the name. But all the lines of force which enter the armature on one side from the pole-piece pass out into the air on the other side, and complete their path through the air; therefore the armature has two poles. The name unipolar is also given to that type of dynamo in which the inductors always cut the lines of force in the same direction; whereas in all other types the inductors pass north and south poles alternately. The term is inappropriate even in this case, since the field exists between two pole-pieces, and the author has suggested the name *continuous pole* for these machines;* but unipolar is shorter, and probably too deeply rooted to be changed. This type of dynamo is interesting as being the only one which generates a direct current without a commutator; and the "winding" is the simplest possible form, since it consists of a *single* inductor in the form of a cylinder or disk of metal. For this reason, however, the *E.M.F.* is limited, it being shown in the paper just cited that it would require an armature about 18 feet in diameter to generate 130 volts at 200 revolutions per

* "Unipolar Dynamos for Electric Light and Power," a paper by F. B. Crocker and C. H. Parmly, *Trans. Amer. Inst. Elec. Eng.*, vol. xi., p. 406, 1894.

minute; but as armatures of other types are now made 12 feet or more in diameter, this size is by no means preposterous.

Dynamos have been constructed with an odd number of pole-pieces. This is usually the result of splitting one of the poles in two; for example, a three-pole machine may be made with one north pole and two other poles, separated from each other, but both of south polarity, and equivalent to a single south pole.

Ring Winding. — The chief structural difference between armatures depends upon whether the inductors lie entirely upon the external surface, or are carried through the interior of the core. The actual form of the core does not determine the question, since large drum windings usually have ring-shaped cores, the interior of the core being superfluous.

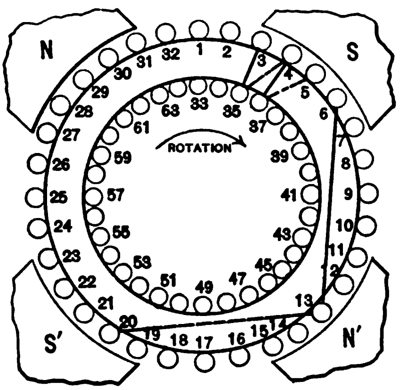

Fig. 93. Diagram of Armature Windings.

In Fig. 93, *CC* represents an armature core carrying inductors 1, 2, etc., and revolving clockwise in a multipolar field formed by the four poles, *N*, *S*, *N'*, and *S'*. If the winding is made up entirely of the inductors 1 to 32 on the outside of the core, the connections merely passing across the ends, as indicated by the line from 6 to 13, a drum winding is obtained. But if the conductors 33 to 64 in the inside of the core are included in the winding, so that an outside inductor is connected to an inside conductor, as represented by the line from 3 to 35, a ring winding is produced.

To generate a higher *E.M.F.* the inductors are connected in series, so as to add their voltages; but to obtain a larger current the inductors are connected in parallel, to add the amperes produced.

The addition of *E.M.F.* by series-connection is secured as follows in the Gramme armature, which is the simplest of the ring type. The inductor 3 is connected with 35, so that the current, which tends to flow toward the observer with right-handed rotation under a south pole, passes back through the conductor 35, and then, by a connection at the rear of the armature indicated by

a dotted line, it goes to inductor 4, through which it is brought forward again under the pole *S*, and so on, until the winding extends completely around the core, and is closed at the starting-point. The entire winding could be made of one piece of wire, but it is more convenient to make it in sections connected together. The conductors 33 to 64 on the inside of the ring cut no lines except those due to a slight magnetic leakage; hence practically no *E.M.F.* is generated in them. Their only function is to complete the circuit, and carry the current back to the successive inductors. It is also a fact that no *E.M.F.* is produced in the neutral spaces between the pole-pieces. The inductor 1, for example, is idle at the moment represented, and 3 is just entering the field and beginning to generate. It is therefore evident that starting with inductor 1, the potential gradually rises, each inductor adding a certain amount, until the point 9 is reached, beyond which the potential falls, since the *E.M.F.* is set up in the opposite direction under pole N'; and at inductor 17 the potential becomes the same as at 1. Passing on to 25, the potential rises again until it equals that obtained at inductor 9, and finally decreases to the original value at the starting-point. Thus there are two points of maximum potential, at 9 and 25, and two of minimum potential, at 1 and 17. If four stationary brushes were placed at the points 1, 9, 17, and 25 respectively, so as to touch the winding as it revolved, those at 9 and 25 would be positive, and those at 1 and 17 negative. The four brushes may be connected to two separate circuits; but ordinarily the two positive brushes are connected together in parallel, and also the two negatives, so as to supply a single circuit.

The brushes are applied directly to the winding in some types of dynamo; but usually the winding is tapped off at a number of points, and connected respectively to the segments of a commutator, on which the brushes rest. A similar armature could be used in a bipolar field, there being only one positive and one negative point in that case; but the principle is substantially the same. We may therefore look upon a four-pole dynamo as a combination of two bipolar machines, and a six-pole dynamo as consisting of three bipolar generators, and so on.

Drum-Windings. — The addition of voltage is secured in this case by connecting the inductor 6, for example, with inductor 13

across the front of the armature, as shown, so that the current flows forward in 6 under pole S, and backward in 13 under pole N'. Then by connecting 13 with 20 at the back of the armature, as indicated by the dotted line, the current is brought forward again under pole S'. By continuing this process, and passing ahead each time to the seventh inductor, a complete winding is produced, which closes at the starting-point, and is equivalent to the ring winding described. It is obvious, however, that the conductors on the ends of the core cross each other as the winding progresses, and tend to pile up in an awkward manner, unless very carefully arranged. For this reason the ring armature is more easily represented in a diagram, and is usually simpler to consider in studying the action of the dynamo.

The crossing of the wires in a drum-winding also brings together those having great difference of potential, while in the ring armature the wires differing considerably in potential are far apart. To offset this disadvantage, the drum-winding does not have the "dead wire" which exists in the interior of the ring construction ; but the end-connections of the former are almost as long as the dead wire in the latter.

Cross-connected Armatures. — Either the ring or the drum four-pole armature described requires four brushes to obtain the full current from the armature. But if diametrically opposite points all the way around the winding are permanently connected together, a brush at 1, for example, in Fig. 93, will also receive the current from the opposite point 17 by the cross-connection; hence, two brushes at 1 and 9 respectively will take the whole current generated by the armature. The cross-connection may be made either in the armature itself or in the commutator. In a six-pole dynamo, three points 120° apart are cross-connected, and four points 90° apart in an eight-pole machine, and so on.

Two-Circuit Multipolar Windings. — In the cross-connected windings just referred to, the current has four paths or circuits through the armature, viz., from 1 to 9, from 17 to 9, from 1 to 25, and from 17 to 25 ; and the current which flows out from the brush at 9 would be the sum of four currents generated in the four quadrants of the armature. The same would be true if the two positive as well as the two negative brushes were connected together in parallel, which is usually done if the machine is not cross-

connected internally. In a bipolar winding there are two paths for the current, this being the minimum number for a closed-coil winding. It is also possible to produce a multipolar winding which has only two paths. In Fig. 93, for example, if a drum-winding is made with 30 inductors instead of 32, the connection being made each time to the seventh inductor ahead as before, the result will be that two brushes applied at 1 and 9 will take off the entire current generated, and there will be but two paths through the armature. Furthermore, the voltage will be nearly twice as great as that generated by the winding with four paths, since it is due to 15 inductors in series instead of 8. This form of winding, which is called "two-circuit" by Parshall, and "series-grouping" by Thompson, is produced on any multipolar drum armature when $C = ny \pm 2$, in which C is the number of inductors, n the number of poles, and y is the "pitch" or "spacing;" i.e., the number of inductors which the winding advances at each end-connection. This must be an odd number, being 7 in the winding described.

If C is an exact multiple of the number of poles, that is, $C = nx$, in which x may be odd or even, then a multiple-circuit drum-winding results. The pitch y and the number C in this case must not have a common divisor. In any drum-winding y is slightly greater or less than the distance between consecutive pole-pieces.

Two-circuit, multipolar ring-windings are obtained if

$$S = \frac{n}{2}y \pm 1,$$

in which S is the number of sections or coils in the winding, each of which may consist of one turn or any number, and y, the pitch, may be odd or even. This gives what Parshall calls a "long-connection" winding, in which y is approximately twice the distance between adjacent pole-pieces. The "short connection," in which y has the ordinary value, is produced when $S = ny \pm 2$. In this case y may be odd or even; but, if the latter, the actual pitch used should be alternately $y - 1$ and $y + 1$. This opportunity for long and short connections in a ring armature arises from the fact that a section under a pole-piece can be connected to another either under a like or an unlike pole, since both terminals of the section are accessible. But in a drum-winding an inductor under one pole must be connected to another under an unlike pole.

Two-circuit windings have the advantage that the number of inductors required for a given *E.M.F.* is one-half as great as in a four-circuit winding. On the other hand, the cross-section of the inductors must be doubled for the same current capacity. Windings with four or more circuits are exposed to the danger that if the *E.M.F.'s* generated by the several poles are not exactly equal, currents will play back and forth between the sections. To take an extreme case, assume that the magnetizing coil is broken or short-circuited on one of the field-cores, so that very little *E.M.F.* is generated under the corresponding pole-piece. That portion of the winding will then act as a short circuit on the other sections, and the armature will probably be burned out. This difficulty is practically avoided in two-circuit windings.

Wave and Lap Windings. — It should be noted that the drum-winding described above always advances in the same direction around the armature. This is called wave-winding, because it would have that form if it were taken off of the core and spread out flat. It is also possible to carry the end connections alternately forward and back so that the successive turns overlap each other. For example, in Fig. 93, inductor 8 would be connected to 13; but 13 is then connected back to 6, which is connected ahead again to 11, and so on, producing when completed a lap-winding.

Right- and Left-Hand Windings consist respectively of turns which pass around the core in a right- or left-hand fashion. The coils represented in Fig. 93 as passing from 3 to 35, then to 4, etc., is a dextrorsal helix like the thread of an ordinary screw, and forms a right-hand winding.

Double Windings. — These consist of two entirely distinct windings placed upon the same armature core, and connected respectively to alternate commutator-bars. The brush is thick enough to make contact with at least two commutator-bars, so that both windings are always in circuit in parallel. This construction reduces the tendency to sparking, because only half of the current is commutated at a time, and also because adjacent commutator-bars belong to different windings; so that an armature coil is not likely to be short-circuited by the formation of an arc, or by copper dust, etc., on the commutator. Furthermore, an accident to one winding does not entirely disable the machine.

This method can be applied to any armature, and may be extended to triple or quadruple windings; its only objection is the increased number of conductors and commutator-bars, which is objectionable in small machines, but for large ones might be an advantage.

Open-Coil Windings. — The windings heretofore considered have all been of the closed-coil type, in which the armature conductors are connected together and closed at the starting-point. This is the usual style of winding for direct-current machines, and is universally employed for incandescent lighting, where a steady current is desired. For series arc-lighting, however, a pulsating current is allowable, or perhaps advantageous; and armatures have been extensively used in which the winding consists of a comparatively small number of separate coils, the terminals of which are open until connected to the circuit by the commutator brushes. The Brush and the Thomson-Houston arc-dynamos have open-coil armatures, and the number in use for this purpose far exceeds those of other types; but they are the only important open-coil windings, and will be considered as special types in the following chapter.

Alternating-Current Armature Windings. Single Phase. — As already stated, any direct-current winding can be made to yield an alternating current. Take any point of a bipolar winding, such as a Gramme ring, and follow it as it revolves; its potential is first zero, then rises to a maximum positive value after it has turned through 90°, then decreases to zero again at 180°, reaches a negative maximum at 270°, and finally returns to zero after it has revolved through a complete circle. Another point diametrically opposite to the first will pass through an exactly complementary cycle of changes, one point being positive when the other is negative, and *vice versa.* By respectively connecting these two points with two collecting-rings, on which rest two brushes that form the terminals of an electric circuit, the latter will be supplied with an alternating current.

In practice, however, alternating-current windings are usually made different from those used for direct currents. One distinction is the fact that a single open-coil winding may be, and often is, employed; but the chief difference is the intermittent action of the inductors. In a Gramme ring a certain number of

coils are always active, while those in the space between the pole-pieces are not generating. In this way a practically steady *E.M.F.* is produced by a reasonable number of coils. But for an alternating current it is allowable to have all the coils active at one moment, and all inactive the next, corresponding to the variations in the current. Hence, the windings need only cover as much of the armature as is covered by the pole-pieces. In Fig. 94, which shows a form of winding embodying these principles, the coils *W* are equal in width to the pole-pieces, and also to the spaces between the poles. All the coils are in series, and form a single open-circuit winding, terminating in the collecting-rings *R* and *S*. At the moment represented, the inductors are

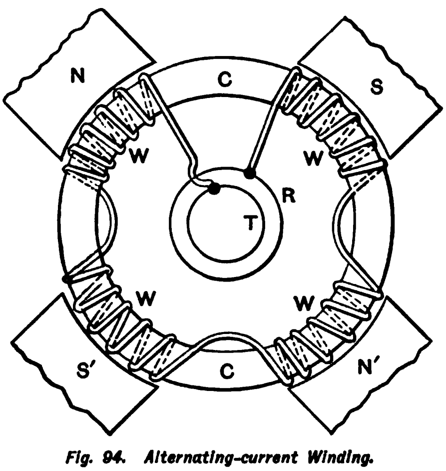

Fig. 94. Alternating-current Winding.

all generating, and the maximum *E.M.F.* is produced, *R* being positive. A rotation of 45°, however, brings the coils into the neutral spaces, and the *E.M.F.* becomes zero, and so on.

Alternating-current armatures may have the same forms as those for direct currents; viz., ring, drum, pole, or disk: they may also be open or closed coil, and single or multiple wound.

Polyphase Windings. — The use of two- or three-phase alternating currents belongs rather to electric power than to lighting; but systems of this kind are being installed for both purposes.

A two-phase armature may be considered as a combination of two single-phase armatures; and, in fact, it usually consists of two entirely distinct windings, each having its own pair of collecting-

rings. The essential feature is the fact that the *E.M.F.'s* generated by the two windings differ in phase by one-quarter of a period, or, in other words, one generates its maximum *E.M.F.* when the other is at zero. For lighting purposes the two currents are supplied to two entirely separate circuits, and each is used just as if the other did not exist. For driving motors the two circuits are combined to produce a rotary magnetic field. If the armature shown in Fig. 94 were provided with another winding, the coils of which were placed in the spaces between the first set, the terminals being connected to another pair of collecting-rings, the result would be a two-phase armature.

Three-phase windings are similar in principle to the two-phase, but produce three currents differing 120° in phase; and, furthermore, the three windings are connected together in either the **Y** or the Δ form. In the **Y** winding the three sets of coils start at a common point, and the three free ends are connected respectively to three collecting-rings, from which the three main conductors of the circuit lead. In the Δ winding the three sets of coils are all connected in series, and the current is tapped off at the three junctions.

Alternators, whether one- two- or three-phase, are often made with stationary armatures and revolving fields. It makes practically no difference in the action, but allows the armature connections to be made solid, the field-current, which represents far less energy, being much more easily supplied through collecting-rings. On the other hand, the field-magnet being usually heavier than the armature, this plan increases the weight of the moving parts.

Alternating-current generators are also built, in which both the field-coils and the armature-coils are stationary, the lines of force from the former being caused to cut the latter by revolving pieces of iron, which carry the lines from one set of coils to the other. These are called inductor dynamos, one type being the Stanley two-phase alternator.

Dynamotor Windings. — A motor and a dynamo are often combined to act as a transformer, as, for example, when a 500-volt direct-current motor is directly coupled to a 110-volt dynamo, the former being driven by current from an electric railway circuit, and the latter furnishing current for incandescent lamps. A similar combination with a dynamo wound for alternating cur-

rents would serve to transform direct into alternating currents, or *vice versa.*

The two functions are often combined in a single machine to secure compactness, in which case the two armature windings are put on one core, and are acted upon by the same field-magnet. Each winding is independent and complete in itself, and is thoroughly insulated from the other. Consequently, any of the forms of winding already described may be adopted, the only peculiarity being the fact that the two windings must be superimposed, or laid side by side in alternate sections. Besides the advantage of compactness secured by placing both windings on the same core, the armature reactions of the two counteract each other, so that demagnetization of the field by back ampere turns, and shifting of the brushes, are both avoided.

A still further simplification consists in using the same armature winding to act as a motor and as a generator at the same time. This is accomplished by connecting the winding to the sections of a commutator in the usual way, and also to collecting-rings. A direct current supplied at the commutator will cause the armature to revolve as a motor, and at the same time an alternating current may be obtained from the collecting-rings. This current will be single- two- or three-phase, depending upon the number of collecting-rings, and the points of the winding to which they are connected. For example, if an ordinary bipolar Gramme winding be connected at four equidistant points (i.e., 90° apart) to four collecting-rings, a perfect two-phase current may be taken off from the rings. Conversely, a two-phase current fed to these rings will enable a direct current to be obtained from the commutator.

Such machines are sometimes called auto-converters, but single-winding converters is sufficiently definite. The term rotary transformer, or rotary converter, is applied to any of these combined motors and dynamos to distinguish them from the ordinary alternating-current transformers, which are called "static transformers." The word static is somewhat objectionable in this connection, and the simple name *converter* should be confined to the rotary types of transformer.

Possible Armature Windings. — The possible forms of direct- and alternating-current windings are almost infinite, and it would

be absurd for the general student, or even the specialist, to attempt to know them all; but the principles involved are quite simple, and with a little study one may understand, or even devise, a winding in a given case.

The chief points are that the windings should be as symmetrical and systematic as possible; wires differing considerably in potential should be kept apart; crossing of wires should be avoided; end-connections should be as short as possible; it is desirable to be able to replace coils without entirely rewinding the armature; and the mechanical construction should be as simple and substantial as possible.

It is obvious that in any of the windings described, each single turn or element may be repeated as many times as desired to increase the *E.M.F.*, but without changing the method of winding. In other words, each line in the diagrams may represent any number of turns of wire.

Balancing Armatures. — A perfectly balanced armature will run so smoothly that one can hardly detect that it is moving at all; whereas the slightest excess of weight on one side, if only one-tenth of one per cent of the total weight, will cause considerable vibration. This produces noise, and constantly jars the machine, which not only strains it, but also causes the brushes to spark.

It is practically impossible to construct an armature core and winding so true that it is balanced; hence armatures are almost always balanced when they are nearly completed. The usual plan is to place the armature with the ends of the shaft resting on two Λ-shaped rails which are perfectly level. It is then rolled back and forth until the lightest point is found by the fact that it tends to remain uppermost. A piece of lead is attached to the armature at this point, the exact amount required for perfect balance being found by trial.

Ordinarily a strip of sheet lead is used, and is held by a band of wire wound around the armature. An effective arrangement invented by Mr. Gano S. Dunn,* consists in inserting pencils of lead in holes provided in the projections of a toothed armature. These weights are securely held in place by wooden plugs in both ends of the hole. It is also obvious that weight may be removed

* U. S. Patent No. 493,375, March 14, 1893.

from the heavy side of the armature in order to secure a balance. This may be done by boring a hole in the core; but this is open to the objection that it connects the disks together, and impairs the lamination. The question is often raised as to whether a standing balance is also a running balance. As a matter of fact, a body balanced statically is also balanced dynamically, provided the weights are symmetrical with respect to the axis of rotation. In Fig. 95 a weight of 2 lbs. at a radius of 1 foot from the axis *AA* will balance a weight of 1 lb. at a radius of 2 feet, whether standing or running, because the static effect and centrifugal force are both directly proportional to the radius, and the weights are in a line perpendicular to the axis *AA*. In Fig. 96 the weights will still balance statically, but not dynamically, since the ends of the axis

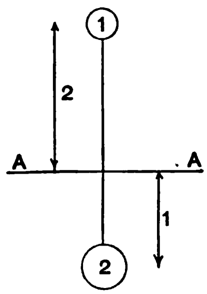

Fig. 95. Static and Dynamic Balance.

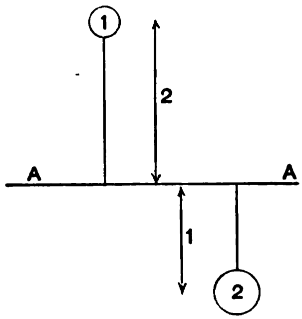

Fig. 96. Static but not Dynamic Balance.

AA will be pulled in opposite directions when running. Ordinarily a weight placed in the middle of an element of the armature will balance it sufficiently well; but if it is necessary to obtain a running balance, it may be found by revolving the armature in bearings which are mounted on springs, or by hanging up the machine, or mounting it on a wheeled truck. Weights are tried at various points until the armature runs perfectly steadily.

Armature Covering and Binding. — Armatures are often covered with canvas in order to protect the conductors from injury by blows or dirt. This canvas is stretched tightly and smoothly over the entire armature, or merely over the ends, in some instances only the end next to the commutator being covered, on account of its exposure to copper dust. This canvas is painted or varnished, to make it impervious to dirt and moisture.

The canvas is held by bands of wire known as *binding-wire.* For this purpose steel, phosphor bronze, or other metal which has great tensile strength and is a poor electrical conductor, is used, since there is a tendency for eddy currents to be set up in these bands. For the same reason a small wire about .03 to .05 inch in diameter is employed. These bands of wire are $\frac{1}{2}$ to 1 inch wide, and about 3 inches apart, and are wound on strips of mica, to insulate them from the conductors. The ends of the wire are secured by small straps of thin brass folded around the band and soldered.

It is particularly desirable that the armature should lose its heat as rapidly as possible, in order to keep down its temperature; and any covering interferes with the dissipation of heat. For that reason armatures are often left uncovered; and in some cases special means of ventilation are provided, such as fans or openings in the armature core. This exposes the armature to moisture and dust, by which the conductors are likely to become short-circuited in time, unless they are very thickly insulated; or in the case of bare copper bars, the spaces between them should be sufficient to prevent the accumulation of dirt. As a general rule, small armatures should be covered; but large ones may be left open, provided they are constructed in the manner stated above. Even when the armature is not covered, binding-wires are required to hold the conductors, and prevent them from being thrown out by centrifugal force, except in armatures with slots, which are made so narrow at the top that the conductors cannot fly out. In this last case wooden sticks may be forced into the tops of the slots, which gives an excellent finish, and dispenses with any covering or binding-wires.

Commutators. — To obtain a direct current from an armature winding, we have already seen that a commutator is required. A commutator for a closed-coil winding usually has a large number of bars, the maximum average voltage between adjacent bars being usually limited to nineteen volts, while for the open-coil — Brush or Thomson-Houston — armature, the commutator has a small number of sections. The former type of commutator is composed of a number of bars of copper *B*, held together by nuts *NN*, and washers *WW*, screwed on the ends of central tube *TT*, as shown in Fig. 97. The bars are insulated from the washers by

mica, as represented at *MM* and *DD*, and each bar is insulated from its neighbors by sheets of mica *E*. The bars must also be insulated from the tube *T*, either by a tube of mica *C*, or by a sufficient air-space. It is very important to have the parts of the commutator perfectly fitted together and screwed up extremely tight, in order that there shall be no interstices or looseness. The ends of the sections of winding may be connected to the projections *P*, by inserting them in the slots *F*, and firmly binding them in place by the screw *H*, as shown in the small detail view. The end of the wires and the screw *H* may then be soldered to make them still more secure, and they may be released at any time by simply applying a hot soldering-iron to them. Solder

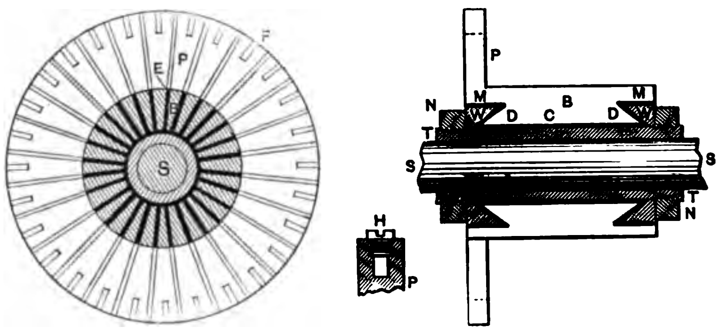

Fig. 97. Construction of Commutator.

alone is not sufficiently reliable for holding commutator connections. The mica insulation extends outward between the projections *P*, in order to prevent copper dust from getting between them. The construction shown is substantial and effective, but it is often modified considerably. For example, the projections *P* may consist of strips of sheet copper set into slots in the end of the commutator-bars, and bent around the wires at the outer end. These are somewhat liable to break off, however; and dirt is likely to accumulate between them unless they are covered with canvas or a disk of fiber. Many commutators are made with the washers *WW* entirely outside of the ends of the copper bars, so that the effective length or face of the commutator is just that much shorter. The undercut form of bar shown in the figure gives so much greater useful surface, however, that it is usually preferable.

The objection urged against it is that it cannot be allowed to wear below *MM*, whereas the other form of bar may be worn down almost its entire depth; but it is questionable if any such amount of wear is permissible, since the surface of the commutator becomes too small. The best material for commutator-bars is simple rolled copper rods of the proper cross-section, and cut off in suitable lengths, since they are tough and of uniform texture. But these cannot be made with projections such as *P*, hence drop forgings or castings are used. The latter are not usually of sufficient toughness and uniformity, and require to be annealed or treated in some way. The use of brass, iron, steel, or other metal except nearly pure copper, has not usually resulted in success, for the reason that these metals seem to burn more than copper under the influence of sparking. Attempts to substitute other insulating materials for mica have also been unsuccessful in most cases. The commutator of the Siemens-Halske dynamo, the bars of which consist of the armature conductors themselves, is so large, being sometimes twelve feet in diameter, that the heat is dissipated to such extent that cardboard insulation is used between the bars. The commutators for open-coil armatures will be described in the next chapter in connection with the Brush and Thomson-Houston arc dynamos, as they are peculiar to these machines.

Brushes. — The principal kinds of commutator brushes which have been used are: —

1. A simple strip of springy sheet copper, the ends of which are slit to insure contact at several points, and set almost perfectly tangent to the commutator. These are used on the Brush and Thomson-Houston arc dynamos in which the current is limited to ten amperes.

2. A laminated brush composed of a number of strips of thin sheet copper soldered or otherwise held together at the end farthest from the commutator. These brushes are called "tangential;" but actually they are beveled off at the end, and inclined to the true tangent in order that the ends of all the sheets may make contact.

3. A laminated brush similar to the preceding, but with the sheets placed perpendicular to the axis of the commutator. The objection to this brush is the fact that it tends to wear grooves in the commutator. This brush is also placed at an inclination to the tangent.

4. A rectangular bundle of copper wires soldered together at one end. This form is likely to cause the same trouble as the last, but not to the same extent. Its position is also inclined to the tangent.

5. Sheets of fine copper gauze are folded or rolled up, and pressed into rectangular form. These brushes make a very perfect contact by reason of their

soft, spongy nature, but they are quite expensive. They may be inclined to the tangent like the three preceding forms, or they may be set radially. The latter position gives the advantage that the point of contact does not change as the brushes wear away.

6. Slabs, blocks, or rods of carbon similar in material to those used in arc lamps. This is a considerable departure from the original form; nevertheless, they are called brushes. They may be set either radially, or inclined to the tangent, usually the former.

Carbon brushes tend to keep the commutator smooth, in fact, they actually polish it; whereas copper brushes tend to tear and roughen the surface. The amount of wear is also less, and a commutator will last several times as long with carbon brushes. The commutator may be reversed, and run in either direction with carbon brushes; but this advantage applies more to motors than to dynamos. Carbon dust is far less objectionable than copper dust about an electrical machine, since it does not produce such a bad short circuit. The chief merit in carbon brushes is the reduction in sparking, which results partly from their smoothing action, and partly from the *gradual* shutting off of the current which occurs when each commutator-bar leaves the brush, owing to the higher specific resistance of carbon. Copper, on the other hand, has such a high conductivity that the full current flows to each commutator-bar, even when it has almost entirely passed from under the brush; and then it is very suddenly interrupted, causing a spark, which would not be produced if the current were gradually shifted to the next commutator-bar.

This explains the paradoxical fact that a certain amount of resistance is desirable in a brush. But as this resistance is only required in the trailing edge of the brush, attempts have been made to increase the conductivity of other portions by combining copper sheets or wires with the carbon.

In addition to the high resistance of carbon brushes, which is decidedly objectionable except in one edge, they are too easily broken, and, having no flexibility, the least roughness, vibration, or dirt will throw them out of contact with the commutator; nevertheless, they are generally preferred unless the amount of current is too great for their conductivity. The use of rollers instead of brushes to make contact with the commutator has often been tried, but has not been successful owing to the small area of contact.

The relation between pressure, contact resistance, and fric-

tion of copper and carbon brushes has been investigated by Messrs. Cox and Buck,* who give data for calculating the values of these quantities in any given case. The results are set forth in the form of curves, one of which shows that the contact resistance of a copper-leaf brush is only about .01 ohm per square inch at 2 lbs. pressure, while that of a carbon brush is about .1 ohm, or ten times as great. It was also found, contrary to the generally accepted idea, that the resistance of a copper brush is very little increased by slightly oiling the commutator, whereas the friction is reduced to less than one-third of its original value.

Brush-Holders. — The devices used for holding the brushes against the commutator with the proper pressure differ in each type of machine, and no general rules can be laid down. The requirements to be fulfilled by a brush-holder are more numerous and difficult than one would expect. The brush must be held securely, and at the same time it must be fed forward as it wears away. It must be capable of being lifted away from the commutator, and held out of contact by some form of catch. The brush should be easily removable for cleaning or renewal. The spring pressure must be adjustable.

One of the most serious troubles with brush-holders results from the current passing through the spring, which destroys the elasticity of the latter by heating it. This may be avoided by insulating one end of the spring, or by carrying the entire current directly from the brush itself to the main conductors by a flexible copper strip or cable firmly connected to both, in which case the brush-holder is not relied upon to conduct any current.

The brush-holders proper are carried upon a *rocker arm*, which is mounted upon one of the main bearings, or upon a support specially provided for it, and is arranged to revolve concentrically with the shaft, so that the position of the brushes may be shifted back and forth until the minimum sparking is obtained.

The only satisfactory way to study brush-holders is to examine the actual mechanisms in use.

FIELD-MAGNET CONSTRUCTION.

General Form. — The form of the field-magnet depends primarily upon whether it is bipolar or multipolar. If the former,

* *Electrical Engineer* (N.Y.), Aug. 7, 1895.

it is usually of the simple horseshoe type, which is difficult to improve upon, although numerous peculiar forms have been proposed, and many have been used for special purposes. The horseshoe magnet may be placed as it is in the original Edison dynamos (Fig. 112), or it may be turned with the pole-pieces upward (Fig. 113), often called the "inverted horseshoe." The term *undertype* is frequently applied to the former, and *overtype* to the latter, on account of the position of the armature. Some designers have put the horseshoe form of magnet on its side, as represented in Fig. 98, the object being to produce a machine in which the armature is neither as low as it is in the undertype, nor as high as in the overtype; but such a machine is unsymmetrical, and not particularly pleasing in appearance. Moreover, the entire base of the machine and the bearings are connected to one of the pole-pieces, and the large surface thus exposed increases the magnetic leakage.

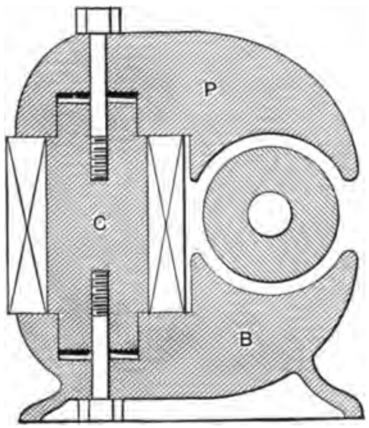

Fig. 98. Bipolar Field-Magnet with Single Coil.

This type is interesting from the fact that it only involves a single magnetizing coil. The same form is also arranged to stand with the core horizontal, the armature being either over or under the latter. In this case the bearings must be supported upon arms of brass or other non-magnetic metal, since they extend from one pole-piece to the other. This form, as well as the undertype, is open to an objection if set upon an iron base, as the latter would act as a magnetic short circuit, and rob the armature of a large fraction of the flux. This difficulty is reduced in Edison machines by interposing thick pieces of zinc between the pole-pieces and the base; but even with this construction Hopkinson* found the magnetic leakage through the base to be 10.3 per cent of the total flux. The other form is ordinarily used without an iron base-plate, the pole-pieces being provided with feet, upon which the machine rests.

* Paper on "Dynamo-Electric Machinery," *Phil. Trans. of Royal Soc.*, May 6, 1886.

The overtype, on the other hand, has small magnetic leakage, because the pole-pieces are not near the base or other magnetic conductor, and their surface is less than that of the undertype or the single coil magnet shown in Fig. 98. Fig. 99 represents a radically different form of bipolar field-magnet. This is commonly called the Manchester type, from the fact that machines of this kind were designed by Dr. John Hopkinson, and manufactured by Mather & Platt in Manchester, England. This construction is extremely solid; but it has the undesirable feature that there are two magnetic circuits in parallel, producing what are called *consequent poles*, and each circuit requires as many ampere turns as a single (horseshoe) magnetic circuit. This also has considerable magnetic leakage, the entire base and bearings being connected to one of the pole-pieces, the same as in Fig. 98.

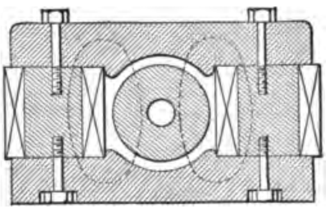

Fig. 99.
Manchester Type of Field-Magnet.

These five types, with slight modifications, are almost the only forms of bipolar field-magnet in general use.

Multipolar field-magnets naturally afford more opportunity for variation in design. Notwithstanding this fact, the tendency has been to adopt one or two types almost universally. The most generally accepted form consists of an external ring with inwardly projecting cores terminating in pole-pieces, as shown in Fig. 116. This construction has the advantages of strength, simplicity, symmetrical appearance, and minimum magnetic leakage, since the pole-pieces have the least possible surface. The external ring is often octagonal in form for a four-pole magnet; but as the number of cores become greater the ring is usually made circular. This enables machines with any number of poles to be built, having the same general appearance; and a change in the number of poles does not involve any serious modification in design. This form of multipolar field-magnet leaves little to be desired, but other arrangements are sometimes used. For example, a multipolar field may be produced by combining two or more horseshoe magnets, as indicated in Fig. 100. This construction possesses the advantage that both magnets may be bolted directly to an iron

base, since the parts *A* and *B* are the yokes or neutral portions of the magnetic circuit. The four-pole magnet in Fig. 101 is a simple arrangement, since only two coils are required; but the base is magnetic, and the two poles *N* and *N* being indirectly magnetized,

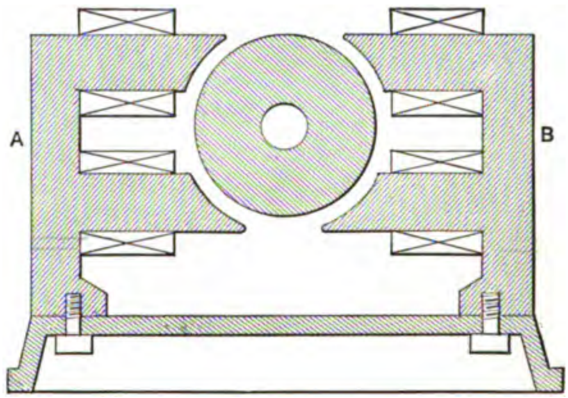

Fig. 100. Double Horseshoe Field-Magnet.

and not having any coils of their own, are not as powerful as the poles *S* and *S*, and the magnetic lines are more easily distorted in the former, which causes sparking. This construction is thoroughly compact and substantial, however, and has been used

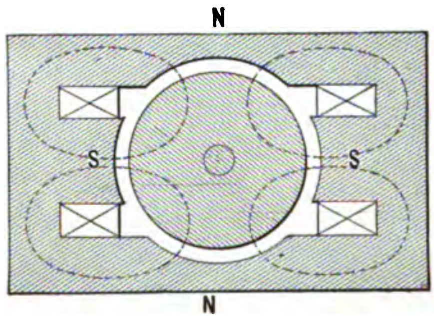

Fig. 101. Multipolar Field-Magnet with Two Coils.

where space is limited, or where a machine is exposed to mechanical injury, as in mining-work.

Material for Field-Magnets. — The principal materials utilized for the purpose are wrought iron, cast steel, and cast iron, which can be used singly or in combination.

Wrought iron has the maximum permeability of any material, although cast steel is often claimed to be equal, if not superior, to it; but in practical manufacturing, cast steel is usually considered to have about 90 per cent of the permeability of wrought iron, as determined by Hopkinson. The only objection to the use of wrought iron for field-magnets is the difficulty of making in the forms required. This may be avoided by using it in simple forms, such as the plain cylinder *C* in Fig. 98, which can easily be made by cutting off lengths from round bars, the latter being very cheaply manufactured in rolling-mills. Another method, by which more complicated shapes of wrought iron can be made, is that of drop-forging in dies or ordinary forging. The employment of drop-forgings has been set forth by the author,* and ordinary forgings have been advocated by Mr. Alton D. Adams.†

The cheapening and development of the process of casting "mild" steel (soft steel) with a very small amount of carbon has resulted in the very general adoption of this metal for field-magnets. It combines high permeability, cheapness, strength, and the ability to be made in any reasonable form. It is generally conceded that it is not economical to use cast iron for the *cores* of field-magnets, since it requires from 2 to 2.5 times the cross-section of wrought iron or steel for the same reluctance. With a circular cross-section this requires about 1.5 times the length of wire for a given number of ampere turns, and the necessary weight of cast iron being 2 or 2.5 times greater, makes up for its lower cost per pound. For pole-pieces, yokes, bases, or other parts which are not wound with wire, the extra circumference is not so objectionable; and often the increased weight is positively advantageous in giving greater stability. Consequently cast iron is often used for these parts, and steel or wrought iron for the cores.

In joining the cast iron to these other metals, it is hardly sufficient to butt the two together, as represented in Fig. 99, as the permeability of a given area of cast iron is only one-half as great. Hence, to secure the proper surface of contact

* "The Perfection of Stationary Electric Motors," *Trans. Amer. Inst. Elec., Eng.*, vol. viii., p. 187.

† A paper and discussion on "The Best Metal for Magnet Frames," read before the Amer. Inst. Elec., Eng., Jan. 16, 1895.

the pieces of steel or wrought iron should be imbedded in the cast iron by placing the former in the mold, or the cast iron may be bored out to receive the ends of the cores, as shown in Fig. 98. Another plan is to interpose a plate of wrought iron of larger diameter than the core, to distribute the magnetic lines. Joints in the magnetic circuit are not desirable, because they involve work in fitting them together, and may cause looseness or weakness; these should not exist, however, with good workmanship. But the common idea that joints introduce great reluctance is not true. An ordinary joint is equivalent to an air-gap of about .005 centimeter, or .002 inch, according to Ewing,* which is practically insignificant, and does not at all warrant the making of complicated castings or forgings to avoid one or two joints in the magnetic circuit.

Size and Form of Field-Magnet Cores. — The length of cores required for a given field-magnet depends simply upon the amount of field-winding. The turns needed are calculated in the manner described on the next page, and the size of wire is found by the method given on page 308. It then only remains to make the core long enough to properly receive these turns, and expose sufficient surface to prevent the temperature from becoming excessive. The last question is discussed on page 313. The cores should be made as short as possible compatible with allowable heating, in order to shorten the magnetic circuit, and reduce the cost of the machine.

The area of cross-section of the field-cores is determined by the total flux; since a flux density of 14,000 to 16,000 lines per square centimeter is the practical maximum for wrought iron, and 6,000 to 7,000 for cast iron.

Having ascertained the length and area of cross-section of the core, the form is easily decided upon; since in every case it should be a *simple cylinder*, unless there is some special and powerful reason for making it otherwise.

Any departure from a circular cross-section is objectionable for the following reasons: —

1. The circle has the least circumference for a given area, even the perimeter of an equivalent square being about 12 per cent longer; and a rectangle with one side three times the length

* *Magnetic Induction in Iron and Other Metals*, **London, 1892, pp. 273–280.**

of the other has a perimeter nearly 30 per cent greater than that of an equal circle.

2. It is much easier to make a cylinder, since it can be turned in a lathe.

3. Cylindrical spools are more easily made than elliptical or rectangular ones.

4. The operation of winding is much more difficult with a rectangular core, since the strain on the wire is very unsteady.

5. A rectangular, or even an elliptical core, is much more likely to cause a short circuit between the turns of wire; since they are forced together at the corners, and cut through the insulation.

Similar arguments apply to a core having a curved axis, that is, those having ring or bow-shaped field-magnet cores.

These latter are far more difficult to wind, and possess little or no compensating advantage. The shortness of magnetic circuit which is claimed for them is very doubtful, for the reason that the actual length of core required is greater than if it were straight, with the winding in the form of a perfect helix. It often happens, in the design of dynamos, that it is apparently desirable to adopt a core which is not circular in section, or has a curved axis; but it is better to change the entire design, to avoid these forms, except, perhaps, for a special machine, to fit in a certain limited space.

Calculations of the Ampere Turns Required in the Field-Coils.— The methods given for determining the flux in a magnetic circuit are often roundabout and difficult, because, as already stated in the beginning of this chapter, the reluctance depends upon the flux density; consequently, it is necessary to find or approximate the flux before the value of the reluctance can be substituted in the formula. This almost amounts to the solution of the problem being dependent upon itself. As a matter of fact, this difficulty can be entirely avoided in most cases by simply fixing the number of lines of force which are to be used in a given case, this being one of the important facts which it is best to settle by calculation or assumption in the very beginning. The next step is to allow a sufficient cross-section of iron to carry these lines of force, with a reasonable flux density. Knowing the latter at once fixes the value of the reluctance, and the necessary number of ampere turns is found by solving the equation. If it be found that this particular solution is not exactly suited to the various conditions, a slight

change in the original assumptions will bring it to the proper value. The inexperienced engineer or student usually makes the mistake of being afraid to make a calculation for fear that it may not give the best possible result. As a matter of fact, the more preliminary calculations that are made, the more perfect and reliable will be the final figures; and it is always wise to make assumptions on both sides of the accepted value before being satisfied that it is the best one. The ampere turns required for the three portions of the magnetic circuit — the field-magnet proper, the air-gap, and the armature core — are determined separately. By thus keeping these quantities independent, a change can be made in one without affecting the others. In the case of each of these parts, we have the required : —

$$\text{Ampere turns} = \frac{10}{4\pi} \cdot N \cdot \frac{L}{A\mu} = \frac{NL}{1.257\,A\mu},$$

in which N is the total flux in lines of force in that portion of the eircuit (see Magnetic Leakage on next page), L is the mean length in centimeters of the lines in the given part, A is the area of cross-section of that part in square centimeters, and μ is the permeability of the material which is obtained by dividing the value of H by the value of B obtained from the curves in Fig. 91, provided the value of B, the flux density, is known. The latter should be fixed in the first place as already explained, and is equal to N, the total flux, divided by A, the area of cross-section.

The proper density to allow depends upon circumstances; but usually about 14,000 lines per square centimeter for wrought iron, in the field or armature core, 13,000 for cast steel, and 7,000 for cast iron, are reasonable values. The density in the air-gap is given by most authorities as about 5,000 lines per square centimeter;* but there is little reason for this limit, as the same authorities † state that the length of the air-gap should be considerable, in order to prevent sparking. As a matter of fact, for this purpose high *density* is fully as effective as length in the air-gap, and it has the additional advantage that it gives a greater output for a given size of armature and pole-piece, and often greatly facilitates the design of a dynamo.

* *The Dynamo*, by Hawkins and Wallis, p. 73.
† *Ibid.*, p. 382.

Magnetic Leakage. — The determination of the flux in different parts of the magnetic circuit should take account of the fact that considerable magnetic leakage occurs. The exact predetermination of the amount of leakage is very difficult. The principles and methods are given by Professor S. P. Thompson.* Mr. Alfred E. Wiener, in a long series of articles,† gives an elaborate discussion of the calculation of magnetic leakage. The correctness of his methods are open to question, however, because he attempts to substitute "simple and practical formulas" for the logarithmic formulas of Forbes and Thompson. But as the leakage is actually a logarithmic function of the distances between the magnetic surfaces, the simpler method is probably only approximate at best.

Experimental determinations of magnetic leakage in various forms of dynamo have been made by Hopkinson,‡ Ives, § Puffer, ‖ and Frisbee and Stratton. **

The last-named investigated the important matter of the effect of the armature current on magnetic leakage, most of the previous tests having been made without any current in the armature. They found that the influence of armature reaction was entirely different in the various types of machine.

The leakage coefficient v is the ratio of total flux to useful field; or, in other words, it is the number of lines in the field-magnet divided by those which pass through the armature. There is considerable magnetic leakage from the field-cores, as well as from the pole-pieces, hence the flux is not constant throughout the field-magnet. Usually the maximum flux exists in the middle of each field-coil, but often the measurement is made at the middle of the yoke. It would seem best either to take the average flux in the field-magnet in calculating v, or to find the actual flux in each part.

In calculating the ampere turns required for the field-magnet itself, it is necessary to multiply the armature flux by v in order

* *The Electromagnet*, London and New York, 1891, p. 173.

† "Magnetic Leakage in Dynamo-Electric Machinery," *Electrical Engineer* (N.Y.), beginning Aug. 22, 1894.

‡ *Phil. Trans. Roy. Soc.*, 1886.

§ *Electrical World* (N.Y.), vol. xix., p. 11, 1892.

‖ *Electrical Review* (Lond.), vol. xxx., p. 487, 1892.

** *Electrical World* (N.Y.), Feb. 16, 1895.

to obtain the field flux, which in turn determines the magnetic density and reluctance in that part of the circuit.

Methods of Field-Winding. — Having calculated the number of ampere turns required for a given field-winding, the next step is to determine how the exciting current shall be obtained. The accompanying diagrams represent the five principal methods of winding the field-magnet, *F.M.* being the field-magnet, *A* the armature, and *E.C.* the external circuit. The direction of the currents is shown in each case by arrows. The separately excited machine (Fig. 102) must be supplied with the necessary field-current from some independent source. This usually consists of a small auxiliary direct-current dynamo, whose only function is to furnish field-current to one or more machines. An alternating-

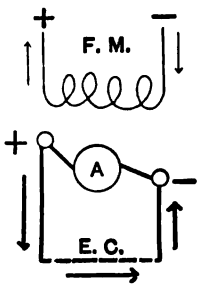

Fig. 102.
Separately-excited Field.

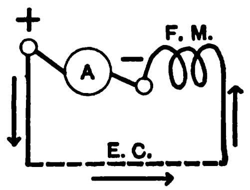

Fig. 103.
Series-wound Field.

current generator is almost necessarily separately excited, its own current not being suitable for producing the field-magnetism. Self-exciting alternators have been made, however, but they really consist of a small direct-current armature incorporated with the main armature. Compound-wound alternators are also partially self-exciting, as explained later. Direct-current dynamos are often separately excited, the object being to make the regulation of the field-current more independent than is possible with a self-excitation. But this extra machine would not be ordinarily desirable except for several large generators in a central station.

The series-wound machine (Fig. 103) is the simplest possible connection; since the armature, field-coils, and line are all in series, and form a single circuit. This is applied almost exclusively to dynamos for series arc-lighting, in which the current, and there-

fore the field-magnetism, are approximately constant. Series-wound machines are also used as motors for railway and other purposes.

In the plain shunt-winding (Fig. 104), the field-coils consist of many turns of fine wire, as indicated; and only a small fraction of the current passes through them, they being in shunt connection with the armature and external circuit. This method is the one most generally used, being applied to dynamos for constant potential lighting and power distribution. Formerly it was used almost universally for these purposes, but compound winding is taking its place both for light and power. For large electric-lighting stations, where hand regulation is required constantly, the plain shunt or separately excited machine is still generally used. Plain

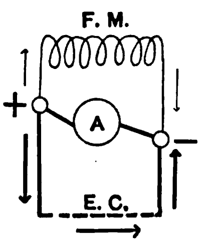

Fig. 104.
Shunt-wound Field.

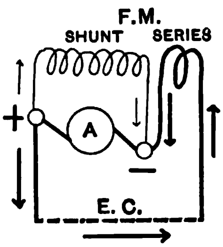

Fig. 105.
Compound-wound Field.

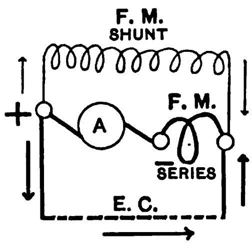

Fig. 106.
Compound-wound Field.

shunt-winding is also usual for constant potential motors. The two forms of compound winding (Figs. 105 and 106) only differ in detail, and are practically the same in action. They consist of shunt-coils of fine wire, as in the plain shunt-winding; but they also have series-coils, which are made up of comparatively few turns of heavy wire carrying the main current of the machine. The direction of the series winding is such that it augments the magnetization produced by the shunt-coils, so that the greater the current drawn from the machine, the stronger the field-magnetism becomes. By properly proportioning the series and shunt-winding, a compound dynamo may be made to preserve a perfectly constant voltage at its terminals; whereas the voltage of a plain shunt dynamo tends to fall considerably with increase of load. A still greater number of turns in the series-coils causes the

voltage to rise when the load is increased, thus making up for the drop or lost pressure on the circuits. This is called *over-compounding*, and is usually designed for a rise of 5 to 10 per cent in voltage from no load to full load.

The séries-coil is sometimes arranged to oppose the magnetizing effect of the shunt-coils, this combination forming what is called *differential winding*. This has been used for motors, and is also applied to dynamos which run at very variable speed, such as those driven by windmills. In the latter case, the effect of the series-coil is to weaken the field if the dynamo runs too fast, and tends to generate an excessive *E.M.F.* The effects of these different kinds of field-winding are shown by what are known as *characteristic curves*, which represent the relation between the *E.M.F.* and the current generated by the machine. The *magnetization* curves are also useful in showing the relation between the *E.M.F.* and the magnetizing current in the field-coils.

Determination of the Size of Wire for Field-Coils. — Having calculated the number of ampere turns required, and decided upon the method of winding, the next step is to find the proper size of wire to employ. It is obvious that a given number of ampere turns can consist of a great many turns carrying a small current, or *vice versa;* and in some cases neither the turns nor the amperes are given by the conditions of the problem, but in other instances one or both may be fixed.

In a separately excited field-winding, usually the *E.M.F.* of the exciter would be given, and the selection of the size of wire would be the same problem as for a shunt-winding. If, on the contrary, the current were fixed, then the solution is the same as for series-winding.

A series-wound machine being almost invariably fed with a definite and constant current, the required number of turns is immediately found by dividing the ampere turns by the given value of the current. The size of wire must be sufficient to carry this current without overheating. This matter of heating will be taken up presently; but as the current is practically always 10 amperes when series winding is used, the size of wire has been found by experience to be between $\frac{1}{10}$ and $\frac{1}{8}$ inch in diameter; that is, No. 10, 9, or 8 B. & S. gauge, depending chiefly upon the depth of the winding.

The determination of the best size of wire for a shunt-winding is far more difficult. The quantities which should be known are the ampere turns required, and the voltage by which the shunt-winding is supplied, i.e., that of the machine. Various methods have been given, but none are very satisfactory. One of the simplest is that suggested by F. B. Corey,* who takes the resistance of one mil-foot of copper wire at 100° F. as approximately 11 ohms. This assumption would be more correct for 98° F.; and, moreover, the allowable rise in temperature for a dynamo is 45° C., or 81° F., above that of the atmosphere, which latter we may take as 20° C., or 68° F. Hence it would be safer to assume the resistance 12.25 ohms at 65° C., as it is most important to have the machine work well at full load. This change will therefore be made in Mr. Corey's figures. The resistance of any copper conductor at 65° C. is therefore $R = \frac{12.25 \times L}{\text{Circ. mils}}$, in which L is the length of the wire in feet. The current flowing in the wire is $C = \frac{\text{Voltage} \times \text{Circ. mils}}{12.25 \times L}$. It is also evident that the ampere turns in any winding are numerically equal to the amperes that would result if a single turn of wire were supposed to be subjected to the given voltage, because two turns would have twice the resistance, and take one-half the current, and so on for any number. Hence: —

$$\text{Ampere turns} = \frac{\text{Voltage} \times \text{Circ. mils}}{12.25 \times l},$$

where l represents the mean length of one turn in feet. By transposition we obtain the cross-section of the wire required: —

$$\text{Circ. mils} = \frac{\text{Ampere turns} \times 12.25 \times l}{\text{Voltage}}.$$

In applying the above formula to a shunt-winding for a dynamo, allowance must be made for the resistance of the rheostat, which is put in the shunt-circuit to regulate the *E.M.F.* This resistance will consume a portion of the voltage amounting to from 10 to 20 per cent. Therefore the voltage substituted in the formula should be 10 to 20 per cent lower than the *E.M.F.* of the machine.

* "A Simple Formula for Magnet Winding," *Electrical Engineer* (N.Y.), Oct. 10, 1894.

The mean length of a turn cannot be determined exactly in the first place; but it can be approximated closely, as windings are usually about 1 in. thick for small machines, and 2 to 3 in. for large ones. A certain length and thickness of coil are required to give sufficient surface to get rid of the heat. (See page 313.)

A more elaborate method is given by Mr. Harrison H. Wood.* Methods are also explained in most of the works on the dynamo.

Construction of Field-Coils. — The operation of winding field-magnets is far less difficult than armature winding; since the number of coils is small, the connections are not complicated, and the coils have a cylindrical or other simple form. The cylindrical form is preferable, as already explained on page 302.

It is desirable to wind the field-coils on some form, spool, or frame, to avoid the necessity of handling the magnet itself. This also greatly facilitates renewing the coils in case of accident or change in voltage. Wooden spools are sometimes used, but they are likely to split or chip off. One of the best forms consists of a tube of tin or brass, which is flanged over at the ends to hold two thick disks of fiber. The tube is covered with two or more layers of fiber or stout paper, to insulate the wires from it. If the coils are wound directly upon the core, the latter should always be covered with several thicknesses of stout paper or other insulation. The ends of the coils must also be insulated in a similar manner, as the cotton covering of the wires is often insufficient to prevent "grounding" of the coils. The actual winding of the wire is a simple operation, but it should be done carefully and *systematically*; that is, in the form of a perfect helix. The time saved by winding the wire in a haphazard fashion is poor economy; as wires are much more likely to become short-circuited if they cross each other at a considerable angle than if they lie parallel, since they cut through or force apart the cotton covering. It is difficult to wind fine wire in a perfect helix; but even in that case winding may advance progressively, and should not skip back and forth.

The only serious trouble in field-winding is in bringing out the ends of the wire. This is especially difficult with the inside terminal, which is ordinarily carried through a hole in one end of the spool, where it is likely to be broken by blows or frequent bending, become short-circuited by pressing against the adjacent

* "Curves for Winding Magnets," *Electrical World*, April 27, 1895.

wires, or become grounded upon the spool or magnet. It should therefore be thoroughly insulated and protected by a stout tube or a wrapping of insulating-tape. It is possible to bring both ends of the wire to the outside by making a turn of one wire for each layer of the other. This is rarely done, however, as it is rather hard to accomplish, and wires of great difference of potential are brought into juxtaposition, tending to break down the insulation. Small wires ought never to be brought out themselves, but should have terminals of flexible cable connected to them, which make two or three turns around the spool before coming out.

The coils in series or compound windings have to carry the main current. Very large wires being awkward to handle, several wires in parallel may therefore be employed for these heavy currents, or sometimes ribbons or strips of sheet copper are used for field-coils. The turns are insulated from one another by tape wound with the copper strip. The inside end is led out by folding it at right angles; or both ends may be brought to the outside by folding the strip in the middle, as represented in Fig. 107, and winding each half as an independent spiral. The two spirals should be separated by a little space, so that they may be insulated by a sheet of fiber or mica.

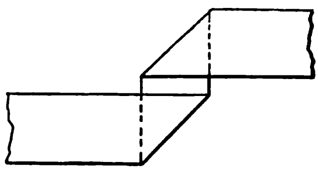

Fig. 107.

Dynamo Bases. — In almost all cases a dynamo is provided with a cast-iron base or bed-plate, which supports the field-magnet and bearings; but some forms of machine stand directly upon the field-magnets, and there is no base-plate; as, for example, in Fig. 98.

The base, when required, consists of a simple plate of cast iron, which is made hollow, and open at the bottom, in order to give thickness without great weight, as represented in Fig. 117. On this base the field-magnet and bearings are firmly bolted, and it should be sufficiently rigid to stand any reasonable strain without the slightest appreciable bending.

The iron base usually rests upon a wooden *base-frame* bolted to the foundations; the former being arranged to slide back and forth upon rails laid upon the base-frame, in order to regulate the

belt-tension by means of screws. A direct-coupled dynamo of medium size is usually bolted directly to the same cast-iron base, or sub-base, as the engine, but often has its own base besides. Very large direct-coupled dynamos may be set on separate foundations; but a cast-iron base common to the two is very desirable unless the coupling be a flexible one.

Dynamo Bearings and Pedestals. — These are simple mechanical constructions of ordinary form. The only peculiarities are their length, which is ordinarily four to six times the diameter of the shaft, on account of the high speed, and the fact that almost all American, and most of the European, dynamos are provided with bearings which are self-oiling by means of rings or other devices, as shown in Fig. 108. The bearings are often made self-aligning by providing the bearing proper with an enlarged central portion of spherical shape (Fig. 108), which is held in a spherical seat formed in the pedestal by turning, milling, or by casting Babbitt or other fusible metal around it, thus allowing the bearing to adjust itself to the exact direction of the shaft. The upper half of the box can be taken off to facilitate renewal, etc., and to permit the armature to be removed.

Fig. 108. Self-oiling Bearing.

The rings shown in the self-oiling bearing revolve with the shaft, and feed the latter with oil continually, which they bring up from the reservoir below. The dirt settles to the bottom; and the upper portion of the oil remains sufficiently clean for a week or more, after which it is drawn off, and a fresh supply poured in through holes provided in the top. These latter are often located directly over the slots in which the rings are placed, so that the bearings can be lubricated immediately by means of an oil-cup if the rings fail to act or the reservoir becomes exhausted.

Large belt-driven dynamos in most cases have a third bearing outside of the pulley, to support the great strain on the latter due to the weight and tension of a heavy belt. This out-board

bearing is simply bolted to an extension of the base like the others. The exact alignment of three bearings requires care and good workmanship, and the slightest error will cause one or more of them to heat. Dynamos having disk or discoidal ring armatures require thrust-bearings to prevent the shaft from moving longitudinally; as a very small displacement sideways would cause the armature to strike the pole-pieces, and would be aggravated by the greatly increased magnetic side pull on the near side. In fact, armatures have often been wrecked in this way. The thrust-bearings in the Brush arc dynamo, Mordey alternator, and others, consist of rings or collars turned or shrunk upon the shaft, and fitting into corresponding grooves in the bearings.

Calculation of Heating Effects in Field-Coils and Armatures. — The design of a dynamo involves the predetermination of the temperature to which the various parts will be raised. This can only be approximate, as it depends upon many conditions, such as the location of the machine, condition of the atmosphere, etc.; but it should be determined as closely as possible. The rate at which heat is produced in the field-coils is a perfectly definite quantity, being equivalent to C^2R watts. This heat will cause the temperature of the coils to rise until the rate at which it is lost is equal to the rate of its production, when the temperature will become stationary. Unfortunately, however, the rate at which the heat is lost cannot be accurately calculated; since it is dissipated by radiation, convection, and conduction, no one of which can be exactly determined.

Experience has shown that a certain rise in temperature is allowable, this being usually put at 40° or 45° C. (72° or 81° F.) above the temperature of the surrounding air. Tests have also demonstrated that this rise in temperature is not usually exceeded if a certain surface of coil is allowed for each watt of power converted into heat. This varies from 1 to 2 square inches of surface per watt lost, depending upon the form, position, and character of the surface, and may be made still less by ventilation. The objectionable effects produced by heat in the field or armature coils are, first, danger of damaging or actually burning the insulation. Second, interference with the regulation of the machine; since the resistance increases .4 per cent for each 1° C. rise in temperature, which would have the effect of considerably

reducing the field-strength of a shunt dynamo. Third, this increase in resistance increases the loss of energy due to the C^2R effect in all the conductors, and thereby lowers the efficiency. Fourth, the expansion due to the heat might cause trouble in the bearings or other parts of the machine.

"The Effect of Temperature upon Cotton and Silk Insulation" has been investigated by Mr. F. C. Reeve,* who finds that neither cotton nor silk is injured mechanically or chemically up to 180° C. (356° F.); this point being very definite. But at a few degrees above this point they are rapidly scorched. This temperature seems extraordinarily high, and does not at all agree with the limit of 65° C. (20° + 45° rise), which is generally adopted in practice. The explanation of this discrepancy probably lies in three facts: first, a temperature of 65°, measured as it is by placing a thermometer against the outside of the coil, indicates a much higher temperature within; second, a factor of safety is required, since a machine *designed* to run at a certain temperature may sometimes become much hotter from overload, accident, hot weather, etc.; and, third, in the experiments of Mr. Reeve the insulation was exposed to 180° C. for several hours, but it is said that a lower temperature, of say 150°, will injure cotton if maintained for many weeks. It is certainly true, whatever the reason may be, that machines which have been designed for a rise in temperature of 60° or 80° C. have often given trouble from overheating. The use of asbestus-covering for wires, instead of cotton or silk, renders the insulation practically indestructible by heat, and encouraging results have been obtained with it; but it is somewhat expensive: this objection, however, may be overcome in time. Strips or bars of copper insulated with mica can also endure a high temperature, and have been used for armature and field coils. But even if the insulation is not injured by heat, it is not at all desirable to run a machine at a high temperature on account of possible injurious effect upon the bearings, commutator, etc.; and the excess of heat indicates low efficiency, which is objectionable in itself.

The calculation of the armature temperature is even more difficult than that of the field, more factors being involved. Heat is produced not only by the C^2R effect in the armature conductors,

* *Electric Power* (N.Y.), June, 1895.

but also by eddy currents and hysteresis in the armature core. Heat generated in the commutator and bearings may also produce considerable effect. Professor Nipher * deduces the following expression for the loss due to eddy currents in laminated armature cores : —

$$\text{Watts lost per cubic cm.} = \frac{\pi^2 n^2 c B^2 a^2 m^2}{4 \times 10^{16}(m^2+1)},$$

in which n is the number of pairs of poles passed per second, c is the conductivity of the iron (reciprocal of specific resistance), B is the induction or flux density in lines per cu. cm., a is the thickness, and ma the radial depth of the plates. The eddy-current loss is proportional to the squares of the speed, flux density, and the thickness of a plate, as shown in the formula.

The calculation of hysteresis has been considered in the beginning of this chapter, but is somewhat uncertain for the reasons there stated. Eddy currents and hysteresis are usually determined by an actual test of the completed machine, their combined effects being called *core losses.*

They can be separated, however, by running the armature at two different speeds; since eddy currents are proportional to the square, and hysteresis to the first power of the speed. If W_1 is the loss due to both at the speed S_1, and W_2 at the speed S_2, x the hysteresis, and y the eddy-current loss at speed S_1, then, —

$$W_1 = x + y \qquad \text{and} \qquad W_2 = \frac{S_2}{S_1}x + \left(\frac{S_2}{S_1}\right)^2 y,$$

from which, by eliminating x, we have,

$$y = \frac{\frac{S_1}{S_2}\cdot(W_2 - W_1)}{\frac{S_2}{S_1} - 1} \qquad \text{and} \qquad x = W_1 - y.$$

It is customary to allow a certain surface per watt lost in the armature. The results obtained by A. H. and C. E. Zimmerman † show that .03 watt is about the maximum amount dissipated for each square inch of armature surface per degree centigrade rise in temperature at a peripheral speed of 3,000 feet per minute, which is an ordinary rate. This is equivalent to about 1.2 watt per square inch for a rise of 40° C.

* *Electricity and Magnetism*, St. Louis, 1895, p. 359.

† "Heating of Armatures," *Trans. Amer. Inst. Elec. Eng.*, vol. x., p. 336.

The dissipation of heat is dependent upon the ventilation effect due to the speed, being given by Hawkins and Wallis * as being proportional to $1 + \frac{v}{2000}$, in which v is the peripheral velocity in feet per minute. The calculation of armature heating is confused by some authorities considering the total surface, and others leaving out the ends of the armature. The watts lost are often taken as those consumed by the C^2R effect alone; eddy currents and hysteresis, which may be nearly as important, being ignored, probably because they are difficult to calculate.

Heating and its effects, when due to some defect or accident, are considered under Diseases of Dynamos, Chapter XIX.

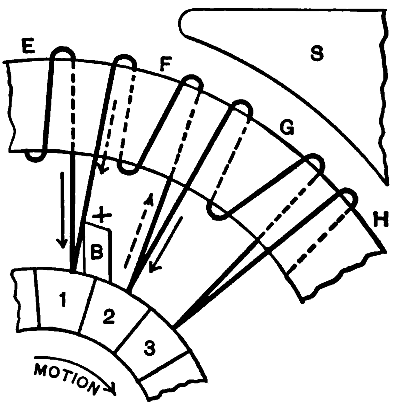

Fig. 109.
Principles upon which Sparking Depends.

The rough rule that wires for field winding should have a cross-section of from 1,000 to 1,200 circular mils per ampere, and armature conductors 600 to 800, is usually approximately correct, providing the thickness of winding is moderate. It serves at least as a guide until the more exact size can be determined by the methods given above, in which the surface is considered.

The Principles upon which Sparking Depends. — The most important precaution in regard to direct-current, closed-coil dynamos is the avoidance of sparking at the commutator. Open-coil machines are made to stand the effects of sparking. There is no trouble in preventing sparking so long as a machine is lightly loaded; but as soon as the current approaches its full value, the tendency to sparking increases, and to avoid it certain conditions are required in the design of the machine. There are also many causes of sparking, due to some defect, or to improper working of the machine; but these will be considered under Diseases of Dynamos, Chapter XIX., confining our attention for the present to those actions which depend upon the original design.

* *The Dynamo*, p. 410.

Fig. 109 represents a portion of a ring armature at the instant when the + brush *B* is touching the two commutator-bars 1 and 2. The coil *F* is therefore short-circuited; and the currents from the two sides of the armature flow out from the coils *E* and *G* into the brush *B*, as represented by the two solid arrows. But the next moment the commutator-bar 2 will leave the brush *B*; and the current will then be obliged to pass through the coil F, as indicated by the dotted arrows. It will require a certain time for this current to establish itself in the coil *F*, due to the self-induction of the latter; and during that time an arc will be formed between the brush *B* and the bar 2 by that portion of the current which does not pass through the coil *F*. This tendency to sparking being caused by the self-induction of the coil, each section should have as few turns as possible. But to obtain a high *E.M.F.*, the total number of turns of wire must be large; and it is not practicable to have more than a certain number of commutator-bars and sections of winding.

Fortunately the sparking can be avoided by the action of the machine itself. If the position of the brush *B* is such that the coil *F* is just coming under the pole-piece *S*, then a certain small *E.M.F.* will be generated in it, and a current will flow through it; since it is short-circuited by the brush, as represented. The direction of this current will be that indicated by the dotted arrows; and if its value is equal to the current in the coil *G*, there will be no self-inductive effect, or tendency to sparking, when it is introduced into the circuit by the commutator-bar 2 passing from under the brush, since there is no change in the electromagnetic conditions. To avoid sparking, therefore, the small *E.M.F.* generated in the coil *F* should be just sufficient to produce the proper "current for reversal" through its comparatively low resistance. To secure this result, the brush is shifted forward through a certain "angle of lead" in a dynamo (and backward in a motor) until the short-circuited coil is brought under what is called the "fringe" of lines of force issuing from the edge of the pole-piece. A precisely corresponding action takes place at the other brush, or brushes, of a bipolar or multipolar machine.

It is evident that if the current in the armature is increased, the current for reversal must increase also, and the brushes should be shifted still farther forward. It is undesirable to be

obliged to adjust the brushes for variations in load, but it is necessary in almost all machines; and the difficulty is greatly aggravated by the phenomenon of *armature reaction,* which is the magnetic effect due to the armature current.

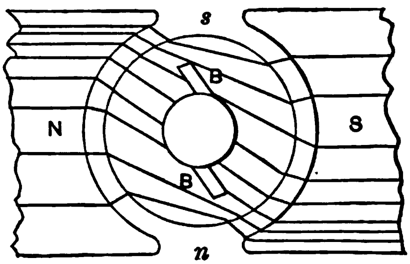

Fig. 110. Armature Reaction.

Armature Reaction. — Any armature becomes an electromagnet while a current flows through its coils. A Gramme ring, for example, taken out of the field-magnet, and supplied with a current equal in value to the full current generated by it, will show strong magnetic polarity at two points corresponding to the position of the brushes. The same *M.M.F.* exists when the armature is running in the field, either as a dynamo or a motor. The effect of this *M.M.F.*, tending to produce poles at *n* and *s*, is to distort the lines produced by the field-magnet itself, and crowd them together at one edge of one pole-piece, and at the opposite edge of the other, as represented in Fig. 110. But if the current in the armature ceases, then the lines become horizontal and uniform.

This distortion is increased and complicated by the shifting of the brushes already explained. Fig. 111 shows the brushes B_1 and B_2 shifted from the line *EF* to the line *JK,* in which case all the armature conductors between the lines *CD* and *GH,* represented by circles with dashes, tend to *oppose* the flux produced by the field-magnet, and are called *back ampere turns;* and all those to the right of the line *GH,* and to the left of the line *CD,* represented by circles with crosses, tend to produce a cross magnetization at right angles to that due to the field-magnet, and are called *cross ampere turns.*

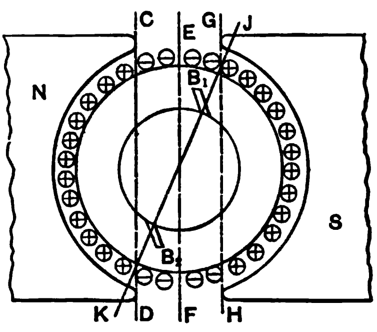

Fig. 111. Cross and Back Ampere Turns.

The back ampere turns must be allowed for in calculating

the ampere turns required in the field winding, and the total number should be increased accordingly.

The cross ampere turns, which tend to increase the flux at the points C and H, and decrease it at G and D, interfere seriously with the production of the current for reversal. Should these cross ampere turns equal the portion of the field ampere turns required for the air-gap, there will be no lines entering the armature at the upper portion of the pole-piece S, and consequently no current for reversal would be generated, hence the sparking would become excessive. It is therefore desirable that the ampere turns on the armature should be considerably less than those on the field. Formulas for the exact relation between them have been given by Esson * and by Swinburne.† This matter is also quite fully discussed by Thompson ‡ and by Hawkins and Wallis. § It is difficult, however, to allow for the various conditions which affect the result in each particular case. The author has already pointed out (page 304) that the so-called "stiff field," i.e., high *M.M.F.*, required in the air-gap for the reasons just explained, may be obtained fully as well by high density as by increasing the air-gap.

Various methods have been devised to compensate for the cross turns, such as that developed by Professor H. J. Ryan, ‖ which consists in providing the machine with "balancing coils" that have the same number of turns, and carry the same current, as the armature conductors, but are opposite in their magnetizing effect, thus neutralizing the armature reaction. This and other devices, such as auxiliary "reversing magnets" and the Sayers winding, are quite fully treated by Professor D. C. Jackson in his *Text-Book on Electromagnetism and the Construction of Dynamos.* The use of carbon brushes reduces the tendency to sparking, by gradually starting the current in the short-circuited coil, owing to the considerable resistance of the brush, as already explained on page 296. The subject of the prevention of sparking is well treated by Mr. Gano S. Dunn.**

* "The Theory of Armature Reactions in Dynamos and Motors," and † "Some Points in Dynamo and Motor Design," *Journal Inst. Elec. Eng.*, vol. xix.

‡ *Dy. Elec. Mach.*, Fourth Edition, p. 74. § *The Dynamo*, p. 351.

‖ "A Method for Preventing Armature Reaction," *Trans. Amer. Inst. Elec. Eng.*, vol. xii., March, 1895, also *Electrical Engineer*, Dec. 25, 1895.

** "Direct Current Motor and Dynamo Design," *Electricity* (N.Y.), Dec. 12, 1894.

Methods of Regulating Dynamos. — The *E.M.F.* of a shunt or a separately excited direct- or alternating-current machine can be very perfectly and conveniently governed by inserting a rheostat or variable resistance in circuit with the field winding. By increasing or decreasing this resistance the field-current, and therefore the *E.M.F.*, are reduced or raised. This resistance is usually controlled by hand; but attempts have been made to operate it automatically by electromagnetic devices, which have not, however, been very successful.

The shunt-coils of a compound-wound dynamo are regulated in the same manner as in a plain shunt machine. The series-coils act automatically to slightly increase the flux and *E.M.F.* in proportion to the load or current.

The current of the constant-current dynamos used in series arc-lighting is governed by special regulators adapted to each particular type, and described in connection with them in Chapter XVIII.

An ingenious method of regulating a constant-current dynamo consists in driving it by a steam-engine having no speed-governor. If the steam pressure and current generated by the dynamo are properly adjusted to each other in the first place, then the current will be kept constant so long as the steam pressure does not vary, for the reason that any increase in current will cause a slowing down of the engine, and *vice versa*. The combination of the two machines is therefore self-regulating, and the engine-governor and dynamo-regulator are both eliminated. This arrangement is in successful operation on the docks of the American Line, New York City. Peculiar regulating devices such as "boosters" are described in the second volume, under Electrical Distribution, where they naturally belong.

The Insulation Resistance of Armature and Field Windings. — The current carried by the armature or field conductors should never be allowed to pass into the cores, not only because of loss of energy, but to avoid the complete breaking down of the insulation which would be almost certain to occur if any leak is allowed to exist. In the case of high-tension machines it is imperative to have the conductors perfectly insulated from the frame of the machine, to avoid the danger of shock to those who tend it. Therefore, a certain minimum insulation resistance

should be maintained between the conductors and the cores or frame. This standard is usually put at one megohm for low-tension machines of about 100 volts, and correspondingly higher for greater *E.M.F.*

Besides the mere insulation resistance, it is necessary to consider the point at which the insulation will break down entirely. A test might show, for example, an insulation resistance of 10 megohms, but it might be punctured and destroyed if 500 volts were applied to it. It is therefore necessary to make a "break-down test" also, at a potential from two to five times the voltage for which the machine is intended.

The voltage required to break down cotton and silk covered wires, fibre, mica, etc., has been investigated by Canfield and Robinson; * the data in regard to the latter materials have also been determined by Steinmetz † and others.

The effect of moisture on the insulation resistance has been studied by T. T. P. Luquer, ‡ and the effect of temperature by F. C. Reeve. §

* *Electrical Engineer*, March 28, 1894.

† *Trans. Amer. Inst. Elec. Eng.*, vol. x., p. 85, 1893.

‡ *Electrical Engineer*, Dec. 28, 1892.

§ *Electric Power* (N.Y.), June, 1895.

CHAPTER XVIII.

TYPICAL FORMS OF DYNAMO FOR ELECTRIC LIGHTING.

THE types of dynamo used in electric lighting are so numerous, and are modified so frequently, that it is useless to attempt to describe all of them. Moreover, the principles laid down in the preceding chapter are intended to enable one to understand and judge any particular dynamo on its merits. An examination of the machines themselves is by far the best way to compare them; and next to that the most definite and complete information regarding the different forms can be obtained from the catalogues of the various manufacturers.

Certain types, however, are so important and interesting, that they deserve a description which will also be of assistance in studying other forms.

The dynamos used in electric lighting may be divided into the following classes: —

A. Direct-Current Machines.

1. *Bipolar, constant-potential for incandescent (and arc) lighting.*
2. *Multipolar, constant-potential for incandescent (and arc) lighting.*
3. *Closed-coil, constant-current for arc lighting.*
4. *Open-coil, constant-current for arc lighting.*

B. Alternating-Current Machines.

5. *Constant-potential for incandescent (and arc) lighting.*
6. *Constant-current for arc lighting.*

DIRECT-CURRENT, CONSTANT-POTENTIAL DYNAMOS.

This is the most common form of dynamo, since it is used for incandescent lighting in nearly every isolated plant and in a majority of the central stations. The current generated by it is also suitable for constant-potential arc lighting, electric motors,

electric heating and cooking apparatus, storage batteries, electrochemical and electrometallurgical purposes, etc.

The armatures of these machines are provided with closed-coil windings of either the drum or ring type. The field-magnets are usually either shunt or compound wound, but in some cases are separately excited. They are bipolar or multipolar in form, resulting in considerable differences in design and appearance; the former will be considered first.

The Edison Dynamo is one of the oldest and most prominent examples of this class. It consists, as shown in Fig. 112, of a horseshoe (undertype) field-magnet, and a drum armature. The pole-pieces are magnetically separated from the base by zinc castings.

This type was formerly employed exclusively in all stations and isolated plants using the Edison system, but is now being replaced to a great extent by multipolar machines for direct coupling with engines, and also for belt-connection. Nevertheless, at the present time there are probably more of these machines in use for direct-current generation than of any other one form. They are simple, substantial, and symmetrical in appearance; but considerable material can be saved by adopting some more modern design.

Fig. 112. Edison Bipolar Dynamo.

The Edison-Hopkinson Dynamo is the Edison type as designed by Hopkinsón, and manufactured by Mather & Platt of Manchester, England. The chief modification is in the form of cross-section of the field-cores, which is usually rectangular. But this is a very doubtful advantage over the circular cross-section, as explained in discussing field-cores on page 302. Hopkinson, however, introduced the great improvement of shortening the field-magnets, and making them of larger cross-section, in place of the long small-diameter cores of the early Edison dynamos. He also showed that the construction of the first large Edison dynamos, with several cores side by side, united to a common pole-piece, was very wasteful of material, since one core of the same total

cross-section would require much less wire. In fact, almost the entire theory of the magnetic circuit, as applied to the design of dynamos and motors, is due to Hopkinson, whose methods are followed to-day.

The Thomson-Houston "Motor Type" Dynamo embodies a horseshoe field-magnet of the overtype. The armature is of the drum form; and since it has a smooth core (i.e., without teeth),

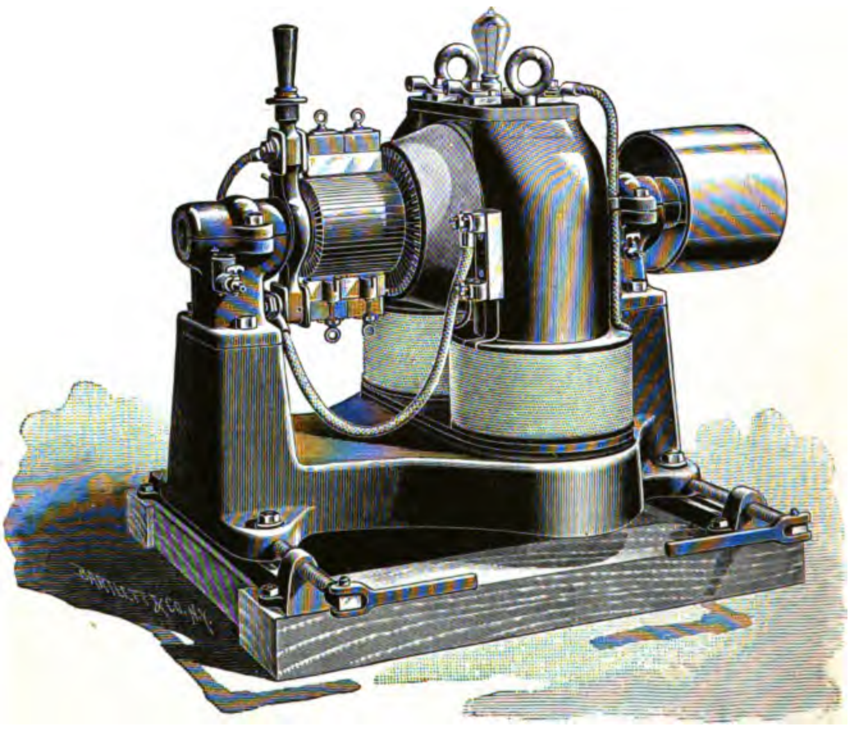

Fig. 113. The Crocker-Wheeler Bipolar Dynamo.

the large number of ampere turns required in the field necessitate long cores, which bring the armature quite high above the base; otherwise this type is similar in general form to that shown in Fig. 113. This type of machine was introduced to replace the "squirrel-cage" field-magnet with spherical armature used in the first Thomson-Houston incandescent lighting machines, which latter had the same general appearance as the arc dynamo (Fig. 119). The name is derived from the fact that the design

was first applied to motors. This type, like the original Edison, is being replaced by the more modern multipolar dynamos of the General Electric Company.

The Crocker-Wheeler Bipolar Dynamo, shown in Fig. 113, is similar in general form to the preceding; but the length of field-coils, and consequently the height of the armature-shaft above the base, are reduced by using a toothed armature, which requires a much smaller number of ampere turns in the field-winding. The armature is of ring form, and therefore relatively larger in diameter than the drum armatures of the two types of dynamo already described. The field-magnets are either drop-forgings of

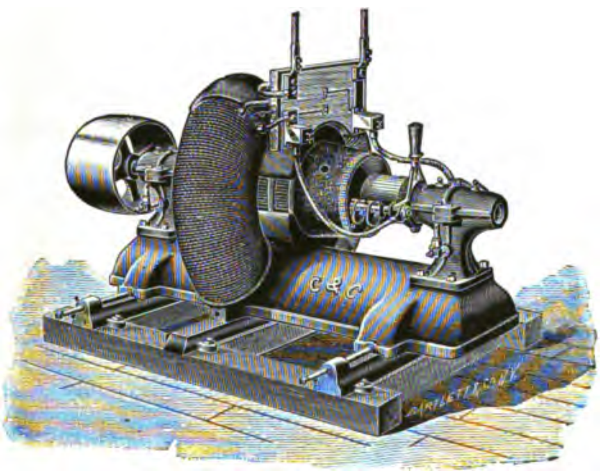

Fig. 114. C. & C. Dynamo.

wrought iron, or castings of steel set into a cast-iron base. These machines are made in sizes of $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$, 1, 2, 3, 5, $7\frac{1}{2}$, and 10 kilowatts capacity, with speeds ranging from 2,000 to 1,000 revolutions per minute respectively. Larger sizes have multipolar field-magnets.

The C. & C. Dynamo is a well-known form, the field-magnet of which is of the Manchester or consequent pole type, having a double magnetic circuit, as illustrated in Fig. 114; the axis of the cores being curved.

The Mather Dynamo is another machine in which the core is curved; in fact, it forms almost a complete ring, as shown in Fig. 115. The objections to field-magnets of these shapes are the

difficulty of winding, as already pointed out on page 303, and also the fact that the field-coils are exposed to injury, since they curve outward beyond the frame of the machine.

English Bipolar Dynamos. — In addition to the Edison-Hopkinson machine already described, a number of bipolar types are built by various manufacturers in England. In fact, comparatively few multipolar forms are used for direct-current service, even large machines of 100 kilowatts or more being made in most cases with only two poles. This is radically different from the practice in the United States, where nearly all dynamos larger than about 10 kilowatts now being manufactured are multipolar.


Fig. 115. Mather Dynamo.

The original "Manchester type," shown in Fig. 99, and designed by Hopkinson, is one of the forms built by Mather & Platt.

Overtype machines, similar in general design to Fig. 113, are made by Laurence, Scott, & Company; Johnston & Phillips; The Electric Construction Corporation ("Elwell-Parker" dynamo); Paterson & Cooper (the "Phœnix" dynamo); the three last, however, having cores of rectangular, instead of circular, cross-section.

Undertype dynamos resembling the Edison form (Fig. 112) are built by Siemens, Brothers & Company, J. H. Holmes & Company (the "Castle" dynamo), and other makers. As an example of this type, we may select one of the large Siemens machines, which has a capacity of 180 kilowatts, at 350 revolutions per minute, being designed for direct coupling with the Willans engine (page 173). Its armature is drum-wound, the diameter being 2 feet, and the length 3 feet. The field-magnets are of the simple horseshoe overtype, with rectangular cores, the cross-section of which is $34\frac{1}{2} \times 16\frac{1}{2}$ inches, being made up of three iron forgings. The total weight of this dynamo is $13\frac{1}{2}$ tons, and of the armature alone nearly $2\frac{1}{2}$ tons.

In addition to the overtype "Phœnix" dynamos mentioned above, these machines are also made in the form represented in Fig. 98, having only a single field-coil.

Multipolar, Direct-current, Closed-coil Dynamos. — In general character and purpose these machines are precisely similar to the bipolar types just described. The field-magnet being multipolar, involves, however, certain modifications in design. The general

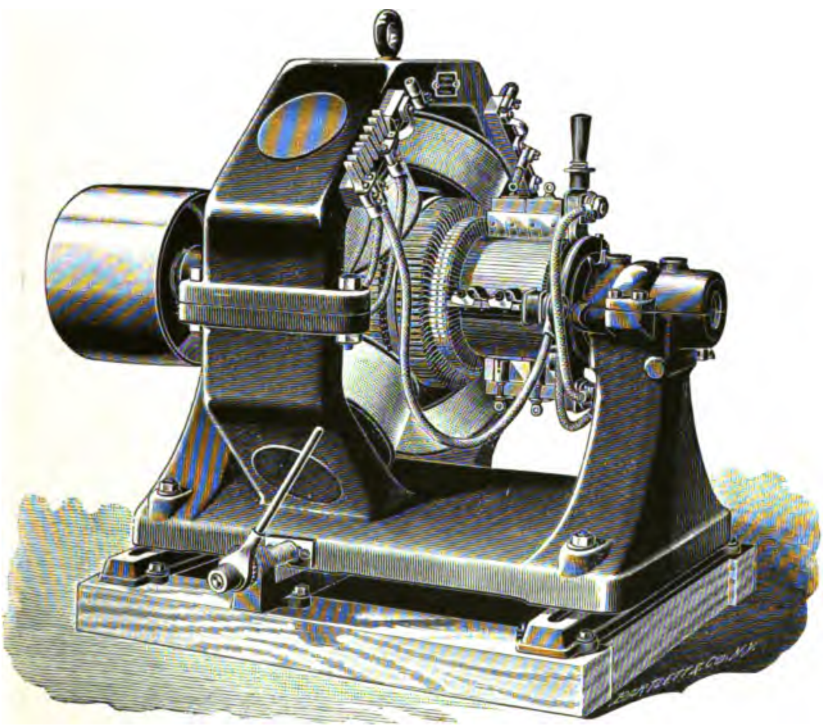

Fig. 116. Direct-current Multipolar Dynamo.

form of multipolar dynamo shown in Fig. 116 has been adopted very widely, and is manufactured by the General Electric, Westinghouse, Crocker-Wheeler, Walker, Eddy, and other companies in the United States, and by the Allgemeine Elektricitäts Gesellschaft of Berlin; the Oerlikon works; Brown, Boveri, and Company; and Alioth and Company of Switzerland, and by other manufacturers in Europe.

The field-magnet ring is often made of circular instead of

octagonal form; and in large machines, particularly when the number of poles is greater than four, this modification is almost universal. The base is also made more massive for larger machines, and the general appearance then becomes similar to that represented in Fig. 122. The advantages of this form of magnet are great mechanical strength, easy construction, compactness, symmetry, effective position of coils, short magnetic circuits, small magnetic leakage, owing to pole-pieces having minimum surface, upper half of magnet easily removed to give access to armature. Machines of any size and number of poles have the same general design, not only for direct, but also for alternating, currents; and either the drum or the ring form of armature may be adopted.

Multipolar Dynamos for Direct coupling with Engines. — The form shown in Fig. 74, which is one of the most prominent of this class, has substantially the same form of field-magnet as the ordinary type of belt-connected multipolar machine represented in Fig. 116. The chief modification consists in the larger diameter of armature, which is necessitated by the smaller number of revolutions per minute, the peripheral speed being thus kept about the same.

This and similar forms of direct-connected dynamos are built by the General Electric, Crocker-Wheeler, Eddy, and other companies.

The various manufacturers of high-speed steam-engines (pages 160 to 178) make certain standard sizes with an extended base and shaft upon which a dynamo of corresponding capacity is mounted, the latter being also specially designed for the purpose. This allows a combination to be made of any type of engine with any style of dynamo, according to preference. The projecting portion of the iron base which carries the dynamo is cast as an integral part of the sub-base of the engine. The engine and dynamo also have a common shaft; hence the construction is thoroughly substantial. These machines, being usually employed for generating currents of low potential and a large number of amperes, are provided with as many sets of brushes as there are pole-pieces, alternate sets being connected together (page 284). The commutator is of large diameter and small width of face, in order to have the necessary surface for the heavy current without increasing the length of the shaft.

Standard sizes of this type are made as small as 20 or 30 kilowatts. For still less capacity, special forms of engine and of multipolar or bipolar dynamo are combined. One of these combinations, shown in Fig. 58, is manufactured in several sizes, from 2½ to 25 kilowatts. These are useful for very small plants, or for supplying a few lamps when the main generators are not running.

The larger sizes of multipolar direct-current generators built by the General Electric Company are represented in Fig. 59. For the most part, these are used in central stations employing the three-wire system of distribution; consequently two dynamos are usually mounted upon a large engine, one at each end of the shaft.

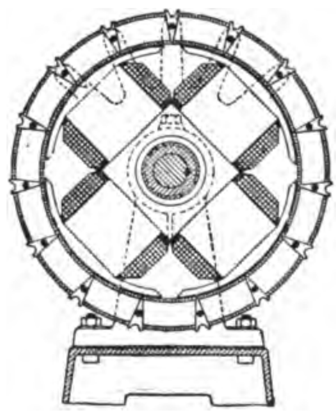

Fig. 117.
Siemens-Halske Internal-Pole Dynamo.

The commutator is formed on the outside face of the armature, being a flat surface perpendicular to the shaft. In fact, the commutator sections constitute part of the armature winding; the principle being that the current can be taken off by the brushes applied directly to the winding, provided the latter consists of bars properly faced and insulated. This reduces the length of the machine by the space which would be occupied by the commutator, and also gives a very large commutator surface. These dynamos may be coupled to compound or triple-expansion engines of the vertical marine type, or to horizontal Corliss engines, which for this purpose are built to run at 125, or even 140, revolutions per minute.

The Siemens-Halske Internal-Pole Dynamo.—This type, which is manufactured and used both in Europe and America, is represented in Fig. 117. The cores of the field-magnet are iron forgings, which radiate outward from a central block of iron which is bolted to the frame of the machine. The figure shows four poles, but larger machines have as many as ten poles. The armature, which is ring-wound, and bolted to the arms of a spider mounted upon the shaft, revolves entirely outside of the magnet. The

winding is composed of copper bars, the interior ones being the inductors, and those outside forming the commutator against which the brushes press. The generators of this type used in the Berlin central stations have armatures over 10 feet in diameter. The advantages of this form are compactness, shortness of magnetic circuit, and large surface of commutator for wear and dissipation of heat.

This dynamo is specially designed for direct coupling with steam-engines; but they are also made for belt-connection. In some cases they are provided with a special commutator distinct from the armature.

The Desroziers Dynamo. — One of the most interesting types of generator is that manufactured by the Maison Breguet of Paris. Its armature is of the disk type, composed solely of the winding, and containing no iron core. The inductors proper are copper conductors arranged radially, and joined one to the other at the center and at the periphery by curved connections. The thin disk armature thus formed revolves in a narrow space between pole-pieces which face each other and are of opposite polarity. The number of poles on each side is from 4 to 10, depending upon the size of the machine, the largest being about 250 kilowatts capacity. These dynamos are built for either belt- or direct-connection, and are extensively used in France.

This form of armature, having no iron core, is entirely free from Foucault currents and hysteresis losses, the self-induction is small, and it has a large surface for ventilation. A very full description of these machines may be found in the *Electrical Engineer* (N.Y.) of Sept. 20, 1893.

DIRECT-CURRENT, CONSTANT-CURRENT DYNAMOS FOR ARC LIGHTING.

These machines were formerly adopted almost universally for arc lighting; but arc lamps are now used with constant-potential, direct, and also alternating, currents, as already stated on page 37. Nevertheless, this type is employed for almost all circuits which supply arc lamps only, the latter being arranged in simple series. Since these generators must produce a constant current (usually ten amperes), even when the number of lamps on the circuit is changed, they are provided with automatic regulators which keep

the current at that value. These consist in almost all cases of electromagnetic devices which either shift the commutator brushes, or vary the field-magnetization in order to control the *E.M.F.* generated, and thus maintain a constant current.

In practice, these machines are usually designed to have considerable armature reaction (page 318), self-induction, and resistance, which tend to prevent the current from becoming excessive when the resistance of the circuit is reduced by cutting out lamps in series. This helps the regulator to control the current, and gives it time to operate in case the current suddenly increases, as it often does. In fact, an arc dynamo must be capable of being completely short-circuited without injury and without any considerable rise in current.

To understand the regulating effect of armature reaction, let us assume that the *M.M.F.* of the field is 12,000 ampere turns, and that the counter *M.M.F.* of the armature is 10,000 ampere turns; then the effective *M.M.F.* which produces the flux through the armature is $12,000 - 10,000 = 2,000$ ampere turns. If, now, the armature current increases from 10 to 12 amperes, the counter *M.M.F.* will become 12,000, equalling the ampere turns of the field, so that the flux, and therefore *E.M.F.*, will be reduced to zero. Hence the current cannot reach 12 amperes, even if the machine is short-circuited. The regulator also acts to make the current still more uniform; but the effect of armature reaction is immediate and reliable, and prevents overheating, even if the regulator fails to operate. The action when the current diminishes is to decrease the counter *M.M.F.*, and raise the *E.M.F.*, which tends to keep up the current. But, unfortunately, the field-magnetism does not discharge as rapidly as the counter *M.M.F.* of the armature falls; consequently, if the circuit is suddenly opened, the *E.M.F.* momentarily rises far above its normal value, causing danger to persons, and straining the insulation. This trouble is mitigated by having the armature core highly saturated, so that the flux cannot be increased very much above its ordinary density.

Each particular type of arc dynamo is peculiar, and requires a special description, which would occupy a chapter or more to be complete. Hence the reader is referred to Thompson's *Dynamo-Electric Machinery*, or other work on the dynamo, where these

machines are fully described, only their principal features being given here. The working of the various arc generators is described in *The Practical Management of Dynamos and Motors*, by Crocker and Wheeler, which treats this subject in detail.

The Brush Dynamo was the first machine to be generally employed for electric lighting. The armature is of the ring form, and consists of a number of separate bobbins wound upon an iron core which has projections on each side. This armature revolves

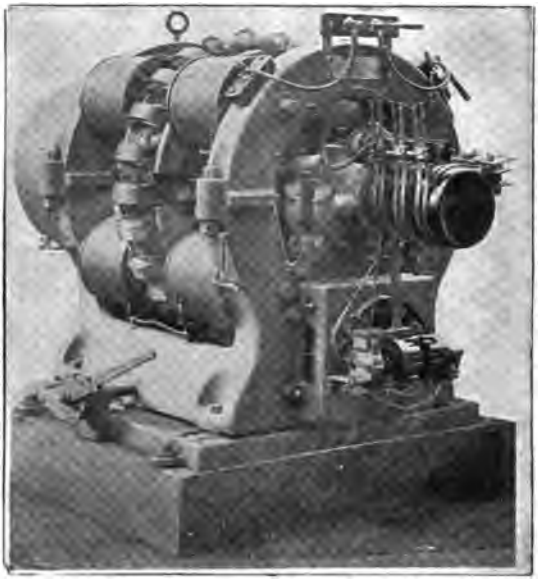

Fig. 118. Brush Arc-Lighting Dynamo.

between the poles of two field-magnets. Usually these are simple horseshoe magnets with two poles, but in the larger machines for 100 lights or more there are four poles on each side (Fig. 118).

Each pair of diametrically opposite armature coils are connected in series, and to an independent pair of commutator sections. By means of the brushes, of which there are ordinarily four or six, the bobbins are connected together, the number of them in series being equal to the number of brushes. For example, in an armature with 12 coils and 6 brushes, there are 3 pairs of bobbins in series. Furthermore, since the commutator

sections of coils at right angles overlap each other about 45°, the bobbins are in parallel twice during each revolution, and are out of circuit the rest of the time.

The Brush regulator, used on all sizes up to and including 65 light (2,000 candle-power nominal) capacity, consists of the so-called "dial," or case, containing a pile of carbon plates. These latter form a shunt to the field-coils, and are pressed together with a lever controlled by an electromagnet connected in series with the main circuit. When the current becomes excessive, the resistance of the carbon plates is reduced by the pressure due to the magnet and lever, which shunts the current from and weakens the field, thus producing the desired regulation. The regulation of the large machines of 80 or more lights capacity is effected by a wall-controller and mechanism for shifting the brushes, and at the same time shunting more or less current from the field-coils as the load varies.

Brush arc dynamos are made in the following standard sizes: Nos. 2, 3, 4, 5, 6, 7, 7½, and 8 being bipolar, and Nos. 9, 10, and 11 having four poles; the capacities of these generators being 1, 2, 4, 10, 20, 30, 50, 65, 80, 100, and 125 lights (2,000 candle-power nominal) capacity respectively. The general advantages of this type, and the exact mechanical, electrical, and magnetic data of the 125 light machine (Fig. 118), also the regulator used on the larger sizes, are set forth in a paper before The National Electric Light Association, March 6, 1895.

The Thomson-Houston Arc Dynamo is used even more widely than the foregoing, and is still more peculiar in construction. The armature is of spherical form, and revolves between two cup-shaped pole-pieces which almost inclose it. The magnetic circuit is completed by the iron rods shown in Fig. 119. The armature was originally made with drum-winding, but ring-winding is now adopted; the external form, however, remains spherical. The armature winding (shown diagrammatically in Fig. 120) consists of only three sets of coils, the turns of each set being connected in series, one terminal of which is connected at a common point, and the other terminals are respectively led to three commutator sections, each occupying nearly one-third of the circumference of the commutator, there being a certain air-space between them. There are two brushes a little distance apart on each side of the

commutator, as represented in Fig. 120, which also shows that at some parts of a revolution there are two coils in series, while at other times one coil is in series with the other two in parallel.

In order to reduce the sparking which is likely to occur with open-coil windings, air-jets are provided which blow against the tips of the brushes, being fed by a small rotary blower mounted on the armature shaft. This provision is obviously necessary for a commutator with only three sections, since the total *E.M.F.* (being 3,000 volts in a 60 light machine) exists between adjacent sections which are separated only about one-quarter inch. This fact also tends to limit the voltage of this type; consequently Brush, Wood, or other machines having a larger number of commutator-bars, are used for capacities greater than 60 lights.

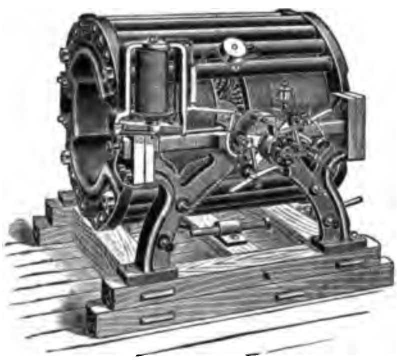

Fig. 119. Thomson-Houston Arc Dynamo.

The Thomson-Houston regulator comprises the so-called wall-controller fastened to a firm perpendicular support near the dynamo, and shown in the upper corner of Fig. 120. This consists of a pair of solenoids in series with the main circuit, which attract upward the cores when the current becomes excessive, thereby opening the shunt circuit P^2P^2, and forcing the main current to traverse the electromagnet *MM*. This causes the latter to raise a lever, which shifts the brushes on the commutator, and brings the current back to its normal value as determined by adjusting the spring. When the brushes are shifted, one moves forward and the other backward in the case of each pair, so that the distance between the positive and negative brushes is reduced, producing a corresponding diminution in *E.M.F.* The action of the machine is stopped by short-circuiting the armature with the switch on the top, which robs the external circuit and the field-coils CC^1 of current, and destroys the field-magnetism. It is allowable for sparks of purplish color, and about $\frac{3}{16}$ to $\frac{1}{4}$ inch long, to be produced at the forward brushes of this machine; but if they become yellow, or of greater length,

or if there are sudden violent flashes, they are due to some abnormal condition. This may be a fault in, or stoppage of, the air-blast, wrong setting of the brushes, bad contact in the wall-controller, regulator lever not working freely, break or short-circuit in the armature coils, or too many lamps on the circuit. The general causes of heating, noise, failure to generate, and other troubles, are given in Chapter XIX. The pulsatory character of the current generated by this machine has been investigated by M. E. Thompson.*

The Thomson-Houston arc dynamos are made in eight standard

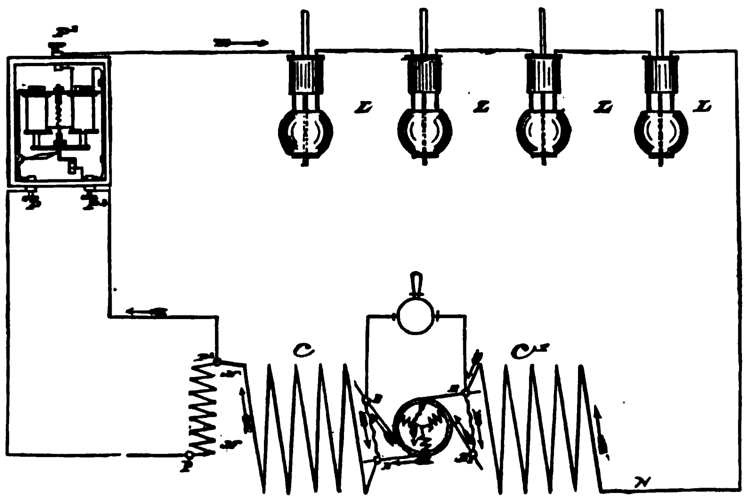

Fig. 119 a. Diagram of Thomson-Houston Arc Dynamo and Regulator.

sizes, having 3, 6, 12, 20, 25, 30, 35, and 50 lights (2,000 candle-power nominal) capacity respectively.

The Wood Arc Dynamo, shown in Fig. 120, differs essentially from the Brush and Thomson-Houston types in the fact that it has a closed-coil armature, and the commutator is made with a great many sections — usually 100 or more. The armature is a true Gramme ring, the core being composed of annealed iron wire. The field-magnet is also one of the characteristic forms employed by Gramme. In fact, this machine is directly based upon the original designs and patents of that inventor; but the

* *Trans. Amer. Inst. Elec. Eng.*, vol. viii., p. 375.

regulator, which is very ingenious and effective, is due to Wood. This consists of an electromagnet, which controls a mechanism that shifts the brushes on the commutator as lamps are cut out of circuit, until finally, when the machine is short-circuited, the brushes are almost 90° from their normal position, and the *E.M.F.* becomes very small. The violent sparking which ordinarily occurs when the brushes are displaced from the neutral points is avoided in this dynamo by practically balancing the *M.M.F.* of the field by that of the armature, so that wherever the brushes may be, practically no *E.M.F.* is generated in the coils which are short-circuited by them. This is shown very clearly in the diagrams

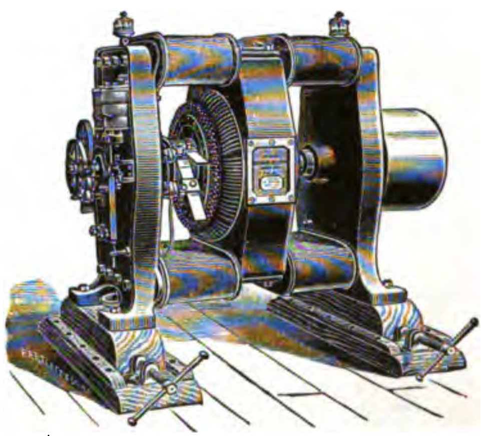

Fig. 120. Wood Arc Lighting Dynamo.

given by Professor R. B. Owens in a paper on a "Test of a Closed-coil Arc Dynamo," * which contains the results of very careful tests on the action and regulation of a 25-light Wood arc dynamo. These machines are made in various sizes up to, and including, 125-light capacity.

The Excelsior (Hochhausen) Arc Dynamo is a well-known type, in which the armature is a closed-coil ring, with quite a large number of sections in the commutator, as in the case of the Wood machine. The field-magnet is of the peculiar form shown in Fig. 121; the fronts of the pole-pieces being carried on hinges, which permit them to swing outward, as represented, to give access to the armature. The current regulator comprises an

* *Trans. Amer. Inst. Elec. Eng., May*, 1894.

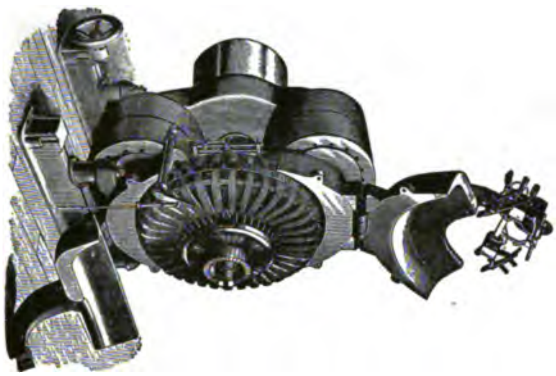

Fig. 121. Excelsior Arc Lighting Dynamo.

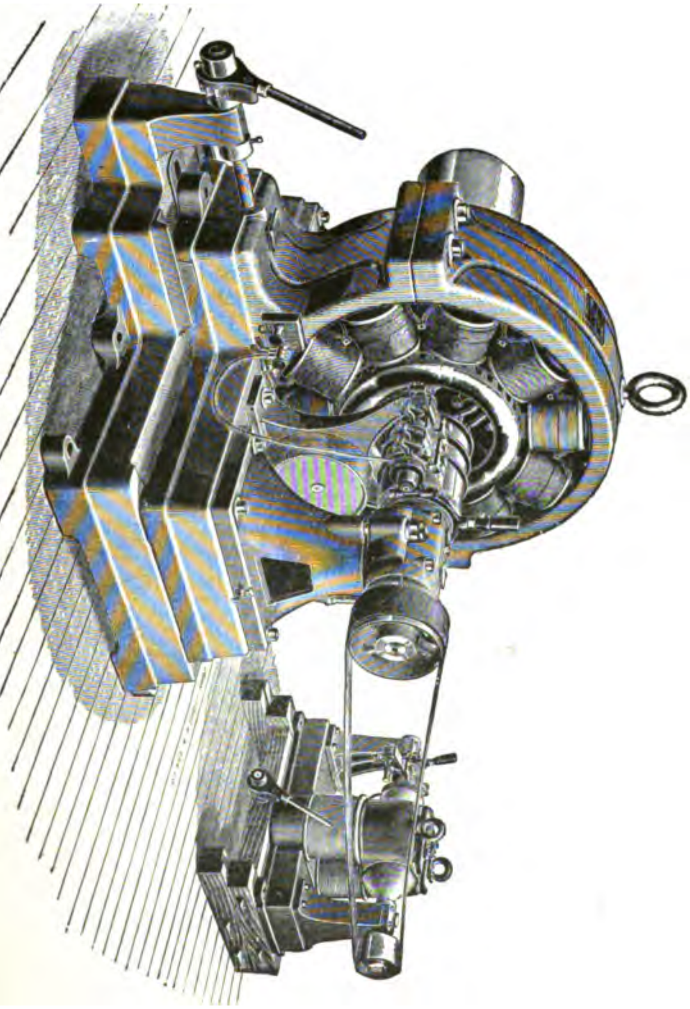

Fig. 122. Thomson-Houston Alternating Current Dynamo and Exciter.

electromagnetic controller placed near the machine, and a small electric motor mounted on the latter. This motor has a pinion on its shaft, which engages with a semicircular rack attached to the rocker-arm, that carries the brushes of the dynamo. The controller acts to send current in one direction or the other through the armature of the motor if the main current rises above, or falls below, its normal value, thereby shifting the brushes until the current is brought back to the proper strength. The rocker-arm is connected by a rod to a switch that cuts into or out of circuit sections of the field-winding, also assisting in the regulation.

This type is manufactured in various sizes, but is especially designed for high voltage, a 200-light machine, generating an *E.M.F.* of 10,000 volts, being described in the *Electrical Engineer* (N.Y.), May 30, 1894.

ALTERNATING-CURRENT DYNAMOS.

The armature windings employed in alternators have already been described in Chapter XVII.; and in general they are simpler than those required for direct currents, since they consist merely of a series of coils corresponding in number to the pole-pieces. The field-magnets are usually quite similar to each other in form, as they are almost necessarily multipolar in order to obtain the necessary frequency, which varies from 25 to 140 periods per second; but in this country is ordinarily between 125 and 140 for electric lighting.

Constant-Potential, Single-Phase Alternators are almost universally made according to the general design shown in Fig. 122 in this country, and also to a great extent abroad. The field-magnet resembles the form widely adopted for multipolar, direct-current machines (Fig. 116); almost the only difference being the fact that in the latter the space between adjacent pole-pieces is only one-third to one-half of the arc covered by each pole-piece, whereas in alternators the spaces and pole-pieces are usually equal in extent. Alternators similar to the form shown are manufactured by the General Electric, Westinghouse, and Fort Wayne Electric Companies, which include about nine-tenths of the single-phase alternators in use in the United States. The field-magnetizing current is usually obtained from a small auxiliary direct-current dynamo called an "exciter."

These machines are also often made with *composite field-winding*, which is analogous to compound winding for direct-current dynamos, and consists in providing the field-magnets with a few turns of coarse wire in addition to the fine wire winding fed by the exciter. The main current generated by the machine is passed through this coarse winding, being rectified or converted into a direct current for the purpose by means of the commutator shown on one side of the collecting-rings in Fig. 122. In this way the voltage may be kept constant, or raised with increased load. Instead of passing the main current itself through the extra coils, it is possible to obtain the same effect by means of a transformer in which the main current acts inductively upon a secondary circuit, and produces a current proportional to itself, which is rectified and used in a similar way.

The Mordey Alternator is a well-known type manufactured in England, and embodies several interesting features. The armature, which is stationary, consists of a number of flat coils that do not contain any iron core. The field is mounted upon a shaft, and revolves. It has only a single coil, to which the magnetizing current is conveyed by contact-rings on the shaft. There are a number of projections from one end of the field-magnet which are all of north polarity, and an equal number of south polarity on the other end. The armature stands in the space between these poles; so that when they revolve each armature coil is subjected to a rising and falling magnetic flux, which does not, however, reverse, since the north poles are always on one side of the armature, and the south poles on the other. Nevertheless, this generates an alternating current, since increasing and decreasing the flux through a coil produces *E.M.F.* in opposite directions. A similar form of machine is built in the United States by the Brush Electric Company.

Other prominent European types of alternator are built by Ferranti, Ganz and Company, and other manufacturers.

Polyphase Alternators belong rather to electric power than to electric lighting, as stated on page 288, where their general principles were explained. Hence typical examples of them will not be described herein.

CHAPTER XIX.

THE PRACTICAL MANAGEMENT OF DYNAMOS.

THE actual handling of the dynamos in a central station or isolated plant is an especially important matter in electric lighting. A work by Dr. S. S. Wheeler and the author [1] is devoted to the selecting, installing, operating, and testing of dynamos and motors, special attention being given to the serious problem of locating and remedying troubles in these machines. The reader is referred to that book for a complete treatment of these subjects, as limitations of space will only allow the principal points to be given in the present chapter.

The Selection of a Dynamo. — One of the first questions that the electrical engineer is called upon to decide is the selection of a dynamo for a certain plant. It depends largely upon circumstances in each particular instance, but there are certain general principles which apply to almost all cases.

Construction. — This should be of the most solid character, and first-class in every respect, including materials and workmanship.

Finish. — A good finish is desirable, — first, because it indicates good construction; second, it stimulates the interest and pride of the attendant; and third, it shows the least dirt or neglect.

Simplicity. — The machine and all its parts should be as simple as possible, and any peculiar or complicated feature should be avoided. These are sometimes successful, but should be well tried and proved before being accepted.

Attention. — The amount of attention required by the dynamo should be small. The screws, connections, and other small parts should be arranged so that they are not likely to become loose, and the delicate parts should not be exposed or liable to injury.

[1] *The Practical Management of Dynamos and Motors*, by F. B. Crocker and S. S. Wheeler, Third Edition, D. Van Nostrand Co., N. Y., 1894.

Handling. — The machine should be provided with an eye-bolt or other means by which it can be easily lifted or moved without injury. It ought to be possible to take out the armature conveniently by removing one of the bearings or the top of the field-magnet.

Interchangeability. — Machines should be made with interchangeable parts, so that a new piece which will fit perfectly can be readily obtained; for this reason regular and established types are preferable to special or unsettled forms.

Regulation. — Some form of regulator should be provided by which the *E.M.F.*, or current, can be reliably and accurately governed.

Capacity. — This should be ample in all cases. It is a very common mistake to underestimate the work required of a given machine; and, even if it has sufficient power at first, the demands upon it are apt to increase, and finally overload it. No one is ever likely to regret choosing a dynamo having a reasonable margin of capacity, since these machines only consume power in proportion to the work they are doing. For example, a 25 kilowatt generator would probably run with a 20 kilowatt load more economically and satisfactorily than a 20 kilowatt machine with the same load.

Form. — The dynamo should be symmetrical, well-proportioned, compact and solid in form. If it is either very tall or very flat, it is usually inconvenient and clumsy. No part should project excessively, or be awkwardly formed or arranged. The large and heavy portions should be placed as low as possible, to give great stability. For the same reason the shaft should not be high above the base, nor should it be so low that there is not ample room for the pully or other attachment. A horizontal belt, for example, will sag and strike the floor if the pulley is very low.

Weight. — The common idea that it is desirable to have a very light dynamo is a mistake when it is for stationary use. There is no advantage in a light machine except portability; and it has the disadvantages of being less strong, less durable, and less steady in running. A sufficient weight to make it thoroughly substantial is obviously a great benefit.

Cost. — It is also a mistake to select a cheap machine, since both the materials and workmanship required in a high-quality

dynamo or motor cost more than in almost any other machine of the same size and weight. It is an undeniable fact that there has been considerable trouble with electrical machinery owing to inferior construction.

In addition to these general considerations, the armature, field-magnets, and other parts of a dynamo, should be made in accordance with the facts given in Chapter XVII.

These suggestions as to selecting a dynamo or motor may be followed when it is possible to make merely a general examination of the machine, or even in cases where it is only practicable to obtain a drawing or description of it. But to make a complete investigation, it is necessary to carry out a thorough test, and measure exactly its various constants.

A satisfactory test cannot usually be made, however, until after the machine is set up in place; and, moreover, it is not generally necessary if it is obtained from a reputable source.

The Number and Size of Units. — The question of selecting the best size and number of dynamos in an electrical plant is not nearly so serious as the corresponding problem in connection with steam-engines; because, as already stated, the efficiency of a dynamo is higher, and is not reduced to anything like the extent at light loads. A dynamo is usually not very much less efficient at one-quarter load than at full load, while a steam-engine is only about one-third as efficient.* There is rarely any necessity, therefore, for running a dynamo at a low efficiency; since it would not require much engineering skill to design a plant in which no dynamo was obliged to operate at less than one-quarter load. It is also a fact that small dynamos of only 50 kilowatts capacity can be made to give an efficiency of 90 per cent, and are nearly as good in this respect as larger machines; so that the electrical generating plant can be subdivided, if desired, without detriment, except the multiplicity of units. It is, therefore, very evident that the size and number of dynamos should be suited to the requirements of the engines, since the difficulty lies with the latter.

A point which is often misunderstood is the fact that the efficiency of a dynamo at full load is not so important as at *average* load. Assume, for example, a dynamo having an effi-

* See page 189.

ciency shown by the curve *OBA* in Fig. 123, and another machine whose efficiency is represented by the curve *OCD*. It would be in accordance with common practice to compare these two dynamos at full load, at which the efficiency of the first is only 85 per cent, while the other gives 90 per cent. But, as a matter of fact, the first machine (*OBA*) is far better than the second; since its *average* efficiency is much higher, and is nearly 90 per cent between one-half and three-quarters of its full power, which would be the range of its ordinary working-load. It should always be remembered that full load is a *limit* which should be

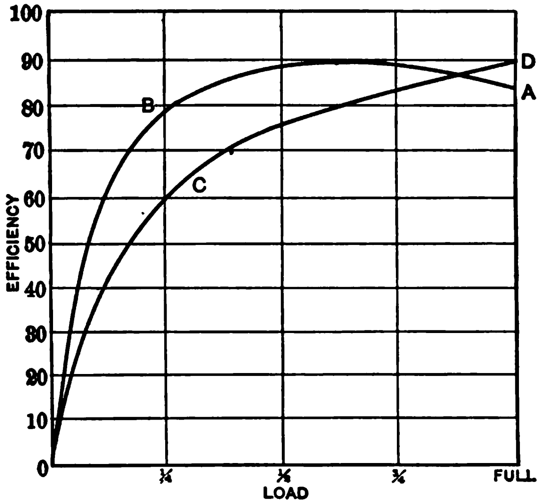

Fig. 123. Efficiency of Dynamos.

but occasionally reached, and then only for short periods of time. Cases might arise in which dynamos would be run steadily at full load, but they would be rare.

Setting up a Dynamo. — The location and foundations for dynamos have already been discussed in Chapter VI., and it will be assumed that they are ready when the machine arrives.

In unpacking and putting the machines together, the greatest possible care should be used in *avoiding the least injury to any part*, in *scrupulously cleaning each part*, and in *putting the parts together in exactly the right way*. This care is particularly important with regard to the shaft, bearings, magnetic joints, and electrical connections, from which every particle of grit, dust, chips

of metal, etc., should be removed. It is very desirable to have machinery assembled by a person thoroughly familiar with its construction; and in the absence of such a person no one should attempt it without at least a drawing or photograph of the apparatus as a guide. An exception may be made to this rule if the machine is very simple, and the way to put it together is perfectly obvious; but in no event should the installation or management of machinery be left to guess-work. The armature must be handled with the greatest possible care, in order to avoid injury to the wires and their insulation, as well as to the commutator and shaft. It should be supported by the shaft, to avoid any strain on the armature-body or commutator. If it is necessary to lay the armature on the ground, interpose a pad of cloth; but it is much better to rest the shaft on two wooden horses or other supports. The proper speed for a dynamo should always be obtained from its manufacturers, and this speed should not be departed from without their approval. Belting, direct coupling, and other means of connecting dynamos with engines, have already been treated in Chapters XV. and XVI.

The direction of rotation of the various machines is sometimes a matter of doubt or trouble. Almost any dynamo is intended to be run in a certain direction; that is, it is called right-handed or left-handed according to whether the armature does or does not revolve like the hands of a clock when looked at from the pulley end. Dynamos are usually designed to be right-handed, but the manufacturer will make them left-handed if specially ordered. This may be required because the pulley to which the machine is to be connected happens to revolve left-handed; or it may be necessary in order to bring the loose side of the belt on top, or to permit the machine to occupy a certain position where space is limited. To reverse the direction of rotation of an ordinary shunt, series, or compound-wound, direct-current, two-pole dynamo, the brushes may simply be reversed, without changing any connection. This changes the point of contact of the brush-tips 180°. If the machine is multipolar, a similar change must be made, amounting to 90° in a four-pole, 45° in an eight-pole, machine, etc. The direction of the current and the polarity of the field-magnets remain the same as before; all that is changed is the direction of rotation and the position of the brushes. This

applies to any machine except arc dynamos and one or two other peculiar machines, which require to be run in a certain direction to suit the regulating apparatus. A separately excited alternating-current dynamo can be reversed in direction of rotation without changing any connection. A self-exciting or compound-wound alternator requires the brushes that supply the direct current to the field to be reversed upon the commutator, and their tips moved through an angle, as above, if the rotation be reversed.

If the direction of the current generated by a dynamo is opposite to that desired, the two wires leading out of it should exchange places in the terminals; or, if this is not desired, the residual magnetism may be reversed by a current from a battery or other source.

DIRECTIONS FOR STARTING DYNAMOS.

General. — The machine should be clean throughout, especially the commutator, brushes, electrical connections, etc. Any metal-dust must be carefully removed, as it is very likely to make a ground or short circuit.

Examine the entire machine carefully, and see that there are no screws or other parts that are loose or out of place. See that the oil-cups have a sufficient supply of oil, and that the passages for the oil are clear, and the feed is at the proper rate. In the case of self-oiling bearings, the rings or other means for carrying the oil should work freely. See that the belt is in place, and has the proper tension. If it is the first time the machine is started, it should be turned a few times by hand, or very slowly, in order to make sure that the shaft revolves easily, and the belt runs in the centers of the pulleys.

The brushes are carefully examined, and adjusted to make good contact with the commutator and at the proper point, the switches connecting the machine to the circuit being left open. The machine should then be started with care, and brought up to full speed, gradually if possible; and in any case the person who starts a dynamo should be ready to stop it instantly if the least thing seems to be wrong, and should then be sure to find out and correct the trouble before starting again. (See "Locating and Remedying Troubles," page 355.)

Starting a Dynamo. — A dynamo is usually brought up to speed either by starting up a steam-engine, or by connecting the dynamo

to a source of power already in motion. The former should, of course, only be attempted by a person competent to manage steam-engines, and familiar with the particular type in question. The mere mechanical connecting of a dynamo to a source of power is usually not very difficult; nevertheless, it should be done carefully and intelligently, even if it only requires throwing in a friction-clutch or shifting a belt from a loose pulley. To put a belt on a pulley in motion is difficult and dangerous, particularly if the belt is large or the speed is high, and should not be tried except by a man who knows just how to do it. Even if a stick is used for this purpose, it is apt to be caught and thrown around by the machinery unless it is used in exactly the right way.

A single dynamo working alone on a circuit without danger of short-circuiting another dynamo or storage battery is easily started and connected to the circuit; but it usually happens in electric lighting, where the number of lamps required to be fed varies so greatly, that one dynamo may be sufficient for certain hours, but two, three, or more machines may be required at other times.

In such cases several dynamos may be connected together, either in parallel (multiple arc) or in series.

Dynamos in Parallel. — In this case the + terminals are connected together or to the same line, and the – terminals are connected together or to the other line. The currents (i.e., amperes) of the machines are thereby added, but the *E.M.F.* (volts) is not increased. The chief condition for the running of dynamos in parallel is that their voltages shall be equal, but their current capacities may be different. Parallel working is therefore suited to constant-potential circuits. A dynamo to be connected in parallel with others, or with a storage battery, must first be brought up to its proper speed, *E.M.F.*, and other working conditions; otherwise it might short-circuit the system, and burn out its armature. In fact, a dynamo should not be connected to a circuit in parallel with others until its voltage has been tested, and found to be equal to, or slightly (not over 1 or 2 per cent) greater, than that of the circuit. If the *E.M.F.* of the dynamo is less than that of the circuit, the current will flow back into the dynamo, and cause it to be run as a motor. The direction of rotation is the same, however, in a shunt-wound dynamo; and no great harm results from a slight difference of potential. In fact, such

machines are self-adjusting, since if one tends to run too fast it has to do more work, and *vice versa;* but compound-wound machines require more careful handling (see page 349).

The test for equal voltages may be made by first measuring the *E.M.F.* of the circuit, and then of the machine, by one voltmeter; or voltmeters connected to each may be compared. Another method is to connect the dynamo to the circuit through a high resistance and a galvanometer; and when the latter indicates no current, it shows that the voltage of the dynamo is equal to that of the circuit. A rougher and simpler way to do this is to raise the potential of the dynamo until its "pilot-lamp," or other lamp fed by it, is fully as bright as the lamps on the circuit, and then connect the dynamo to the circuit. Of course the lamps compared should be intended for the same voltage and in normal condition.

When the dynamo is first connected in this way, it should only supply a small amount of current to the circuit (as indicated by its ammeter), and its voltage should then be gradually raised until it generates its proper share of the total current; otherwise it will cause a sudden jump in the brightness of the lamps on the circuit.

Series-wound Dynamos in Parallel not Used. — If the machine is series-wound, the back current just described would cause a reversal of field-magnetism and a serious short-circuit. In fact, series dynamos in parallel are in very unstable equilibrium; because if either tends to generate too little current, that fact weakens its own field, which is in series, and thus still farther reduces its current, and finally reverses the machine. One way in which this difficulty might be overcome, is by causing each to excite the other's field-magnet, so that if one generates too much current, it strengthens the field of the other, and thus counteracts its own excess of power.

Another plan is to excite both field-magnets by one of the dynamos; but the best method is to connect together the two brushes which convey the current from the armatures to the fields in the two machines, by what is called an "equalizer" (Fig. 124), or "Gramme wire." By this means the electrical pressure at the terminals of the two armatures is made the same, and the currents in the two fields are also made equal. Series machines

are not often run in parallel, but the principles just explained help the understanding of the next case, which is extremely important.

Compound Dynamos in Parallel. — Since the field-magnets of these machines are wound with series as well as shunt coils, the

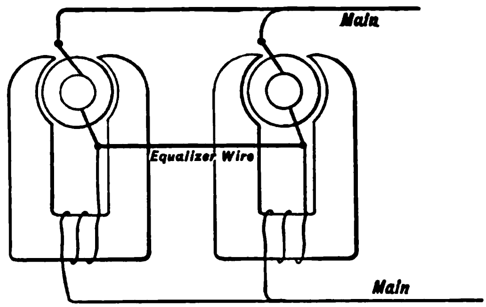

Fig. 124. Series-Wound Dynamos in Parallel.

coupling of them is a combination of the cases of the shunt and the series-wound machines just described.

Fig. 125 represents two compound machines in parallel.

Assume that one machine is already running, that switches F^1 in the shunt circuit, and S^1 in the main circuit, are closed,

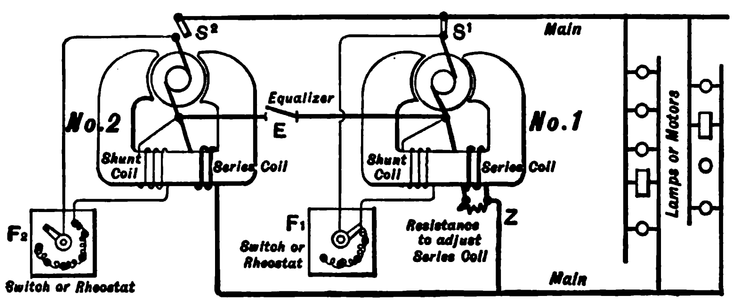

Fig. 125. Compound-Wound Dynamos in Parallel.

and that armature No. 1 is generating its full current, and feeding the lamps on the main circuit, the shunt and series field-coils of the machine carrying their proper current. Now, to throw on the other dynamo, its armature (No. 2) is brought up to normal speed, switch F^2 is closed, which excites its shunt-coil. Switch E, on the "equalizer," is then closed, which excites its series-coil with part of the main current from No. 1. The second machine

should then give its full voltage, and its main switch S^2 is then closed, and the voltage of the machine is regulated to make it produce its share of the current for the main circuit. It is necessary to actually compare the voltage before closing the main switch, regulating it by means of the rheostat F^2 until it is slightly greater at first, so that the machine generates a little current, and then raise it until the machine does its share of the work. With compound dynamos considerable care and a close agreement in voltage are required.

In disconnecting a machine, the same steps are taken in exactly the reverse order. Any number of compound-wound dynamos may be run in parallel in this way; and even those of different size or current capacity may be connected, provided their voltages agree, and provided also that the resistances of their series field-coils are inversely proportional to the current capacities of the several machines. Dynamos which are compound-wound to maintain a constant potential at their terminals work well after their voltages are once made to agree, even with a variable load. But machines which are "over-compounded" to generate a higher potential at greater loads must give exactly the same percentage of increase at full load, and must agree at all intermediate points, otherwise the dynamo which tends to produce a higher voltage will generate more than its share of the current. This may be overcome if the resistance of the series-coil of the machine which tends to take too large a share of the load is slightly increased, by simply interposing a few extra feet of conductor of the same current capacity as the series-coil, and between it and the main conductor or 'bus bar. The shunt which is almost always used to adjust the effect of the series-coils in compound dynamos (shown at Z in machine No. 1, Fig. 125) operates properly in the case of machines working *singly*, but is worthless for machines in parallel, since it affects all the dynamos alike, and simply reduces their voltage equally. Hence a shunt should be used when this latter result is desired; but the action of individual generators should be adjusted by varying the resistance of the series-coils themselves, as described above.

Another difficulty which arises with [illegible]compounded dynamos in parallel, is the fact that when, for example, one machine out of four is working alone at one-quarter of the total load, it

will be fully loaded, and will generate the maximum voltage, while the loss of potential on the conductors is only one-quarter of the maximum. The pressure at the lamps will therefore be too high by an amount equal to three-quarters of the full drop. This very objectionable excess of voltage at the lamps may be avoided by merely leaving the equalizer (switch E, Fig. 125) connected to all the dynamos, so that the currents in the series-coils will be proportional to the *total* load, and not to the load on each machine. In the case of high-potential dynamos, it would be dangerous to have them connected to the circuit when they were stopped for cleaning and repairs, consequently a resistance exactly equivalent to the series-coil should be substituted between the equalizer and the 'bus bar, whenever a machine is disconnected from the circuit. This matter has been quite fully discussed by Professor E. P. Roberts and the author in the *Electrical World*, Oct. 13, Dec. 1, and Dec. 8, 1894.

Alternators in Parallel. — In order that alternators shall work well in parallel, it is necessary for them to agree in voltage, fre-

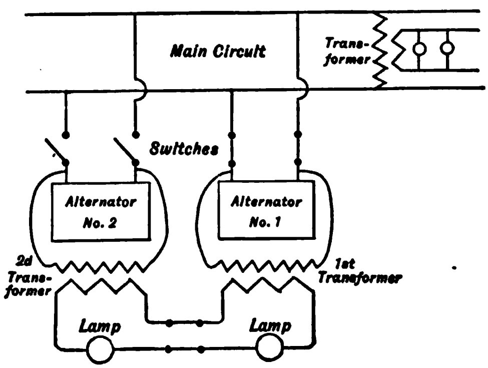

Fig. 126. Alternators in Parallel.

quency, and phase. The form of the $E.M.F.$ waves should also be approximately the same. Self-induction and resistance in the armature circuit of alternators in parallel give flexibility, so that the machines need not run with such exact agreement. On the other hand, this flexibility makes it easier to throw alternators out of synchronism. Another factor is the *definiteness* of the magnetic field, which depends upon the $M.M.F.$, air-gap, distance between the pole-pieces, and armature reaction. This question has

been much discussed, and authorities are not agreed in regard to the best conditions for running alternators in parallel; but it is a fact that many machines are successfully operated in this way.

To throw an alternator into circuit with others, its speed is brought up to the proper point, and its *E.M.F.* is made equal to that of the circuit. The phase may then be determined by connecting two lamps in series with the secondary circuits of two transformers; the primary circuits being fed respectively by the machine to be switched in, and by the others already in circuit.

The secondaries, of, say, 50 volts each, should be connected in series with each other and to two 50-volt lamps. When the phase of the currents of the two machines is opposed, the lamps are dim, and *vice versa*. If the lamps flicker badly, the phase is not right; but if the lamps are steady at full brightness, the machine is in synchronism, and it may be connected, without disturbing the circuit, by closing its main switch.

If dynamos are rigidly connected to each other or to the engine, so that they necessarily run exactly together, there is no need of bringing them into step each time, but they should be adjusted to the same phase in the first place.

Dynamos in Series. — This arrangement is much less common than parallel working, being only applied to series-wound dynamos on arc circuits and to "boosters" (see page 39). The conditions are exactly opposite to those of dynamos in parallel.

To connect machines in series, the positive terminal of one must be connected to the negative terminal of the next; and each must have a current capacity equal to the maximum current on the circuit, but they may differ to any extent in *E.M.F.* The voltages of machines in series are added together; and therefore danger to persons, insulation, etc., is increased in proportion.

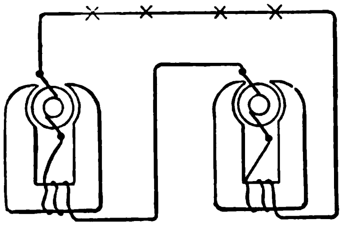

Fig. 127.
Series-Wound Dynamos in Series.

Series-wound dynamos in series are connected in the simple way represented in Fig. 127, but usually machines connected in series are for arc lighting; for example, when two dynamos, each of 40 lights capacity, are run on one circuit of 80 lamps, in which

case the dynamos usually have some form of regulator. These regulators do not ordinarily work well together, because they "seesaw" with each other. This difficulty may be overcome, either by connecting the regulators so that they must work together, or by setting one regulator to give full *E.M.F.*, and allowing the other to control the current. This latter plan can only be followed when the variation in load does not exceed the capacity of the regulating-machine.

Shunt or compound dynamos in series run well provided the shunt field-coils are connected together to form one shunt across both machines. If the machine is compound, the series-coils must be connected in series in the main circuit. Another plan is to connect each shunt-field so that it is fed only by the armature of the other machine; or both the shunt-coils may be connected so as to be fed by one armature, the series-coils being in the main circuit, as before.

Alternators in Series.—The synchronizing tendency which makes it possible under certain circumstances to run alternators in parallel, causes them to get out of step and become opposed to each other when it is attempted to put them in series. It is therefore impracticable to put them in series unless their shafts are rigidly connected together, so that they must run exactly in phase, and add their waves of current, instead of counteracting each other. This is a case that rarely arises in practice.

Dynamos on the Three-wire System (Direct Current).—In the ordinary three-wire system for incandescent lighting, no particular precautions are required in starting or connecting dynamos. As a matter of fact, the two sides of the system are almost independent of each other, and form practically separate circuits, for which the middle or neutral wire acts as a common conductor. There is, however, a tendency for the dynamos to be reversed in starting up, shutting down, or in case of a serious short circuit. This may be avoided by exciting the field-coils of all the dynamos from one side of the system, or by means of a separate dynamo.

DIRECTIONS FOR RUNNING DYNAMOS.

When a dynamo has been properly started, it usually requires very little attention while running; and it often runs well all day without any care whatever.

In the case of a machine which has not been run before, or has been changed in any way, it is wise to watch it closely at first. It is also well to give the bearings of a new machine plenty of oil in the beginning, but not enough to get on the armature, commutator, or any part that would be injured by it; and the belt ought to be rather slack until the bearings have gotten into easy working condition. If possible, a new machine should be run without load, or with a light one, for several hours; and it is always wrong to start a new machine with its full load, or even a large fraction of it. This is true even if the machine has been fully tested by its manufacturer and is in perfect condition, because there may be some fault in setting it up which would cause trouble. All machinery requires some adjustment and care for a certain time to get it into smooth working order.

The person in charge should always be ready and sure to detect the beginning of any trouble, such as sparking, the heating of any part of the machine, noise, abnormally high or low speed, etc., before any injury is caused, and to overcome it by following the directions given on pages 355 to 363.

Special care should be observed by any one who runs a dynamo to avoid *overloading* it, because this is the cause of most of the troubles which occur.

Personal Safety. — Never allow the body to form part of a circuit. While handling a conductor, a second contact may be made accidentally through the feet, hands, knees, or other part of body, in some peculiar and unexpected manner. For example, men have been killed because they touched a "live" wire while standing or sitting upon a conducting body.

Rubber gloves or rubber shoes, or both, should be used in handling circuits of over 500 volts. The safest plan is not to touch any conductor while the current is on; and it should be remembered that the current may be present when not expected, due to an accidental contact with some other wire or to a change of connections. Tools with insulated handles, or a dry stick of wood, should be used instead of the bare hand.

The rule to use *only one hand* when handling dangerous electrical conductors or apparatus is a very good one; because it avoids the chance, which is very great, of making contacts with both hands, and getting the full current directly through the body.

The above precautions are often totally disregarded, particularly by those who have become careless by familiarity with dangerous currents. The result of this has been that *almost all the persons accidentally killed by electricity have been experienced electricians or electrical workmen.*

DIRECTIONS FOR STOPPING DYNAMOS.

Dynamos may be stopped by following substantially the same directions as those given for starting them, but in the reverse order.

A generator operating *alone* on a circuit can be slowed down and stopped without touching the switches, brushes, etc., in which case the current gradually decreases to zero; and then the connections can be opened or changed without sparking or other difficulty.

When, however, a dynamo is working in parallel with others, or with a storage battery, it must not be stopped or reduced in speed until it is entirely disconnected from the circuit, otherwise it will act as a short-circuit. Furthermore, the current generated by it should be reduced nearly to zero before its switch is opened. This is usually accomplished by adjusting the field-regulators of either direct- or alternating-current machines.

A constant-current dynamo may be cut into or out of circuit in series with others, and can be slowed down or stopped, or its armature or field coils may be short-circuited to prevent the action of the machine, without disconnecting it from the circuit. It is absolutely necessary, however, to preserve the *continuity* of the circuit, and not attempt to open it at any point, as it would produce a dangerous arc. Hence a path must be provided by closing the main circuit around or past the dynamo before disconnecting it. The same rule applies to any lamp, motor, or other device on a constant-current circuit.

It will be observed that in all cases the generator should not be disconnected until its current is reduced to an insignificant value; and never, except in an emergency, should a circuit be opened at full or even half load, for the reason that the flash at the contact points, discharge of magnetism, and mechanical shock which result are decidedly objectionable.

Immediately after a machine is stopped, it should be thoroughly

cleaned, and put in condition for the next run; since this can be done much more easily while it is still warm. When not in use, machines should be protected from dirt and moisture by covers of rubber, oiled canvas, or enamel cloth.

DISEASES OF DYNAMOS.

In the work by Dr. S. S. Wheeler and the author, to which reference was made in the beginning of this chapter, the subject of "Locating and Remedying Troubles in Dynamos and Motors" is treated in detail, about seventy pages being devoted to it. It is impossible to devote much space to this matter in the present volume; but its importance is such that the list of possible troubles is herein given, and whenever feasible the symptoms and remedies have also been included.

It is evident that the subject is somewhat complicated, and difficult to handle in a general way, since so much depends upon the particular conditions in any given case. Nevertheless, it is quite remarkable how much can be covered by a systematic statement of the matter.

It frequently happens that a trifling oversight, such as allowing a wire to slip out of a binding-post, will cause as much annoyance and delay in the use of electrical machinery as the most serious accident. Other troubles, equally simple, but not as easily detected, are of frequent occurrence. In such cases a very slight knowledge on the part of the man who runs a dynamo will enable him to overcome the difficulty immediately, and save much time, trouble, and expense.

It should be remembered by those in charge that it is usually better to STOP the machine when any trouble manifests itself, even though the difficulty does not seem to be very serious, because it is very likely to develop into something worse. There are, of course, many cases, particularly in electric lighting, when it is almost impossible to shut down; but even then spare machines should always be ready to be quickly substituted for the defective one. The continued use of faulty apparatus is too common a practice, and is often inexcusable. Neglect and carelessness with any machine are usually and deservedly followed by accidents of some sort.

The general plan here followed is to divide all troubles which

may occur to dynamos into eight classes, the headings of which are the most important and obvious bad effects produced in these machines; viz.: —

1. *Sparking at the Commutator.*
2. *Heating of Commutator and Brushes.*
3. *Heating of Armature.*
4. *Heating of Field-magnets.*
5. *Heating of Bearings.*
6. *Noise.*
7. *Speed too Low.*
8. *Failure to Generate.*

Any one of these general effects is very evident, even to the casual observer, and each one of them is perfectly distinguishable from any of the others, thus eliminating about seven-eighths of the possible cases. The next step is to find out which particular one of eight or ten causes in this class is responsible for the trouble. This requires more careful examination; but, nevertheless, it can be done with comparative ease in most cases.

SPARKING AT THE COMMUTATOR.

This is one of the most common troubles; the objection to it being that it wears, or may even destroy, the commutator and brushes, and produces heat, which may injure the armature or bearings. Any machine having a commutator is liable to it, including practically all direct-current, and some alternating-current, machines. The latter have continuous collecting-rings which are not likely to spark, but self-exciting or compound-wound alternators require a supplementary continuous-current commutator that may spark. This trouble can be prevented in most cases, however, by proper construction and care. The following causes of sparking apply to nearly all machines, and they cover closed-coil dynamos especially.

The very peculiar cases which may arise in particular types of open-coil armatures can only be reached by special directions for each. (See page 334.) A certain amount of sparking occurs normally in most constant-current dynamos for arc lighting, where it is not very objectionable, since they are designed to stand it, and the current is small.

The principles and conditions relating to sparking are given in Chapter XVII. See also article on "Sparking of Closed-coil Dynamos," by G. F. Hanchett, *Electrical World*, Dec. 29, 1894.

1. **Cause.** — *Armature carrying too much current*, due to (*a*) overload (for example, too many lamps fed by the dynamo); (*b*) short circuit on the conductors; (*c*) excessive voltage on a constant-potential circuit, or excessive amperes on a constant-current circuit.

2. *Brushes not set at the neutral point.*

3. *Commutator rough, eccentric, or has one or more "high bars"* projecting beyond the others, or one or more *flat bars*, commonly called "flats," or *projecting mica*, any one of which causes brush to vibrate, or to be actually thrown out of contact with commutator.

Remedy. — Smooth the commutator with a fine file or fine sandpaper, the latter being applied by a block of wood which exactly fits the commutator (be careful to remove any sand or copper dust remaining afterward; *and never use emery*). If commutator is very rough or eccentric, the armature should be taken out and put in a lathe, and the commutator turned off. Large machines sometimes have a slide-rest attachment, so that the commutator can be turned off without removing the armature from its bearings.

In turning a commutator in the lathe, a diamond-pointed tool should be used, having a very sharp and smooth edge, and only an exceedingly fine cut should be taken off each time. The surface is then finished by applying a "dead smooth" file while the commutator revolves rapidly in the lathe. Any particles of copper should then be carefully removed from between the bars. Sometimes a *very little* vaseline, or a drop of oil, may be applied to a commutator which is rough. Too much oil is very bad, and causes the following trouble: —

4. *Brushes make poor contact with commutator;* that is, they touch only at one corner, or only in front or behind, or there is dirt on surface of contact. Sometimes, owing to the presence of too much oil, or from other cause, the brushes and commutator become very dirty. Insufficient pressure also gives poor contact.

5. *Short-circuited or reversed coils in armature.* — The former become heated even after a few minutes' run.

6. *Broken circuit in armature.*

7. "*Grounds*" *in armature* (i.e., accidental contact between the conductors and the core). See paper on "Location of Grounds in Armatures, Fields," etc., read by C. E. Gifford before Amer. Inst. Elec. Eng., June 25, 1895.

8. **Cause.** — *Weak field-magnetism.*

Symptom. — Voltage low, pole-pieces not strongly magnetic, non-sparking point of brushes shifted from normal position.

Remedy. — In a shunt-wound machine this trouble is probably due to a poor contact, or other excessive resistance in the field-circuit.

9. *Unequal distribution of magnetism.* — One pole-tip is much weaker than the other (of the same pole-piece), due to too great armature reaction compared with *M.M.F.* of field-magnet.

10. *Very high resistance brush.* — A carbon brush may have too high resistance to make sufficiently good contact.

11. *Vibration of machine,* usually due to imperfect balance of armature or pulley or to a faulty belt.

12. *Chatter of brushes.* — This occurs with carbon brushes, particularly when they are radial, and if commutator is sticky.

Remedy. — A very little oil will usually stop it.

13. *Pulsations of current.* — Variations in, or surgings of, the current, due to action of engine governor or other cause.

14. "*Flying*" *break, or short circuit, in armature conductors,* which only exists when armature is running, and is usually due to centrifugal force.

HEATING IN DYNAMO.

The degree of heat that is injurious or objectionable in a dynamo or motor is easily determined by applying the hand to the various parts. If the heat is bearable, it is entirely harmless. But if the heat is unbearable for more than a few seconds, the safe limit of temperature has been passed, except in the case of commutators in which solder is not used. In testing with the hand, allowance should always be made for the fact that bare metal seems much hotter than cotton, etc. If the heat has become so great as to produce an odor or smoke, the safe limit has been far exceeded, and the current should be shut off, and the machine stopped immediately, as this indicates serious trouble.

The effect of heat on the insulation of wires, and the temperature at which it is injured, have been investigated by Reeve.* Neither water nor ice should ever be used to cool electrical machinery, except possibly the bearings of large machines, where it can be applied without danger of wetting the other parts.

Determining heat by feeling will answer in ordinary cases; but the sensitiveness of the hand differs, and it makes a great difference whether the surface is a good or bad conductor of heat. The back of the hand is more sensitive and less variable than the palm for this test. But for accurate results a thermometer should be applied, and covered with cloth or waste to keep in the heat. In proper working the surface temperature of any portions of the machine should not rise more than 45° C. or 81° F. above that of the surrounding air. (See page 313.)

It is important to correctly locate the heat in the particular part in which it is produced. A hot bearing may cause the armature or commutator to heat, or *vice versa;* hence all parts should be felt, to ascertain which is the *hottest.* It is much surer to make observations for heating by starting with the machine perfectly cool, and any trouble which is serious is usually perceptible after a run of five or ten minutes at full speed with the field-magnet excited.

HEATING OF COMMUTATOR AND BRUSHES.

1. **Cause.** — *Heat produced in the armature, bearing, or field-coils.*

2. *Sparking.* — Any of the causes of sparking already given will produce heating.

3. *Tendency to spark,* or slight sparking not visible.

4. *Overheated commutator* may disintegrate carbon brushes, and cover commutator with a black film which offers resistance and aggravates the heat.

5. *Bad connections in brush-holder.*

6. *Arcing or short circuit in commutator* across mica, or insulation between bars or nuts.

7. *Carbon brushes heated by the current.* — Carbon brushes require less attention than copper, because they do not "cut"

* *Electric Power,* June, 1895.

the commutator, and their resistance prevents the development of sparking; but this higher resistance causes them to heat more than copper, particularly if they do not make good contact over their entire surface.

HEATING OF ARMATURE.

If the armature of a dynamo is allowed to run as a motor without load, any excess of current taken must be converted into heat by some defect; hence this current is the best indication of the condition of a machine. It is easy to determine whether an armature is hot, even when running, by placing the hand in the current of air thrown off by centrifugal force.

1. **Cause.** — *Excessive current in armature coils.* — The same as Cause 1 for Sparking.

2. *Short-circuited armature coils.* — The same as Cause 5 for Sparking.

3. *Moisture in armature coils.* — Similar to preceding, but armature is more uniformly heated, and gives off vapor. Should be baked for several hours at about 240° F. This may be done in an oven, near a fire, or by passing full current through it.

4. *Foucault currents in armature core.* — This is a matter of first construction. (See page 274.)

5. *Eddy currents in armature conductors.* — Also structural. (See page 280.)

6. *Reversed coils on one side of armature,* which cause a local current to circulate around it. A small current is sent through the armature standing still, and faulty coil will show reversed polarity if a compass is slowly passed around the armature.

7. *Heat conveyed from other parts.* (See Heating of Commutator, Bearings, and Field.)

8. *Flying short circuit between armature conductors,* which only exists while armature is running, and is usually due to centrifugal force.

HEATING OF FIELD-MAGNETS.

1. **Cause.** — *Excessive current in field-coils.* — Reduce the voltage, or increase the resistance, of a shunt-field. If the trouble is due to a short circuit in one coil, that one will be cooler, and

the corresponding pole-piece will be magnetically weaker, than the others with which it is in series.

2. *Foucault currents in pole-pieces.* — A structural defect. (See page 275.)

3. *Moisture in field-coils.* — Similar effect to Cause 1. Treatment as in Cause 3 for Armature Heating.

HEATING OF BEARINGS.

If the bearing is very hot, the shaft should be kept turning slowly, as it might "freeze," or stick fast, if stopped.

1. **Cause.** — *Lack of oil.*

2. *Grit or other foreign matter in the bearings.*

3. *Shaft rough or cut.*

4. *Shaft and bearing fit too tightly.*

5. *Shaft sprung or bent,* in which case it turns with more difficulty at a certain part of its revolution.

6. *Bearings out of line.* — Shaft turns more easily if screws which hold bearing in place are slightly loosened.

7. *Thrust of pulley, collar, or shoulder on shaft against one or both of the bearings.*

8. *Too great strain on the belt.*

9. *Armature nearer one pole-piece, producing greater magnetic attraction on that side.*

10. *Bearing is heated by hot pulley, commutator, or armature.*

NOISE.

A dynamo may seem to make a noise, which in reality is caused by the engine or other machinery to which it is connected, but listening near the different parts will show where the sound originates.

1. **Cause.** — *Vibration due to armature or pulley being out of balance.* (See page 291.)

2. *Armature strikes or rubs against pole-pieces.* — This is detected by placing the ear near the pole-piece, by examining the armature to see if its surface is abraded, or by observing the clearance between the armature and field while the former is slowly revolved.

3. *Shaft collar or shoulder, hub or edge of pulley, or belt, strikes against bearings.*

4. *Rattling due to looseness of screws or other parts.*

5. *Humming, squeaking, or hissing of brushes.* — May be located by placing the ear near the commutator, and by lifting off the brushes one at a time. A little oil usually reduces the noise; but a rough commutator should be made smooth, as described under Cause 3 of Sparking.

6. *Flapping of belt or pounding of joint against pulley.*

7. *Slipping of belt on pulley because of overload,* producing an intermittent squeaking noise.

8. *Humming of armature teeth as they pass edges of pole-pieces.*

9. *Humming due to alternating or pulsating current.*

SPEED TOO LOW.

1. **Cause.** — *Overload.* (See Cause 1, Sparking.)

2. *Short circuit in armature.* (See Cause 5, Sparking.)

3. *Armature strikes pole-pieces.* (See Cause 2, Noise.)

4. *Shaft does not revolve freely.* (See Heating of Bearings, all cases.)

FAILURE TO GENERATE.

1. **Cause.** — *Residual magnetism too weak or destroyed,* due to (*a*) vibration or jar; (*b*) proximity of another dynamo; (*c*) earth's magnetism; (*d*) accidental reversed current through fields, not enough to completely reverse magnetism. Actual reversal of residual magnetism may be very objectionable, as in case of charging storage batteries; but, although the popular supposition is to the contrary, it will not cause the machine to fail to generate.

2. *Reversed connections or direction of rotation.*

3. *Short circuit in the machine or external circuit* prevents the voltage of a shunt-wound dynamo from building up.

4. *Field-coils opposed to each other,* in which case the pole-pieces will be of the same instead of opposite polarity when tested with a compass, a current from some other source being sent through the coils.

5. *Open circuit.* — (*a*) broken wire or faulty connection in the dynamo itself; (*b*) brushes not in contact with the commutator;

(*c*) safety-fuse melted or absent; (*d*) switch open; (*e*) external circuit open.

In all the other cases when a dynamo fails to generate, the field-magnetism is very weak; but it sometimes happens that the magnetism may have full strength, and the only trouble is the simple fact that a switch or other connection is open. This is determined by testing the field-magnets with a piece of iron.

6. *Brushes not in proper position.* — The correct points of contact for the brushes depend upon the particular kind of winding, and no general rules can be laid down. In the absence of definite knowledge, the points on the commutator having the greatest difference of potential, as determined by a voltmeter, are the proper positions for the brushes.

Bibliography of the Dynamo. — The most important papers and articles on this subject have already been referred to in the last three chapters. Among the most useful books relating to the dynamo are the following: —

COX, F. P., *Continuous Current Dynamos and Motors*, N.Y., 1893.

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CHAPTER XX.

ACCUMULATORS,—PRINCIPLES, CONSTRUCTION, AND MANAGEMENT.

ACCUMULATORS, also called storage or secondary batteries, consist of cells in which a chemical change is brought about by passing a current through them, whereby they are made capable of giving back electrical energy by discharging them until they return to their original chemical condition.

In 1802, soon after the invention of the primary battery by Volta, Gautherot demonstrated the fact that platinum wires, after being used to electrolyze saline solutions, were able to produce secondary currents. Volta, Ritter, Davy, Becquerel, and others observed similar effects, the phenomenon being what is commonly called *polarization*.* In 1859 Planté undertook a series of experiments, with the object of studying and magnifying this effect, and finally developed the Planté type of accumulator, which consists simply of lead plates in dilute sulphuric acid. This investigation, as described by its author,† is a model of careful and able scientific work.

The chief difficulty with the Planté battery is the great length of time required for "forming" the plates, which process consists in converting the surface of the lead into active material by repeated charging and discharging of the cells. In 1881 Camille Faure devised the method of pasting the lead oxide or active material directly upon the plates. This largely avoids the tedious forming process; but the plates thus produced are not as durable as the Planté elements, being more liable to disintegration and buckling.

Innumerable forms of accumulator have been invented, and many of them have been exploited, in which copper, zinc, and

* The history and data of polarization are fully treated in Wiedemann's *Elektricität*, vol. ii., p. 642.

† *Recherches sur L'Electricité, par* Gaston Planté, Paris, 1883. Translation by P. B. Elwell, London, 1887.

other metals besides lead, were used; but almost all of those now being manufactured are lead batteries of the Planté or Faure types, or a compromise between the two.

General Principles of Accumulators. — Any primary battery will act as a secondary battery, provided its chemical action is reversible. The ordinary gravity battery, for example, may be regenerated by sending a current through it opposite in direction to that produced by it. The zinc sulphate and metallic copper are thus reconverted into metallic zinc and copper sulphate, the reaction being $Zn\,SO_4 + Cu = Zn + Cu\,SO_4$, which is exactly the reverse of the action as a primary battery. There would be practical difficulties, however, in completely recharging a spent gravity cell by this method; but it could be at least partially accomplished, and the principle is perfectly correct, — in fact, Thomson and Houston have a patent * for this idea.

In some forms of primary battery the chemical reaction liberates a gas that escapes, as, for example, in the Grove cell, in which nitric acid is reduced to nitrous oxide, and passes off as a gas; so that the action is obviously irreversible, and not suitable for a secondary battery.

The Planté battery, upon which nearly all successful accumulators of the present day are based, was originally made by placing two plates of metallic lead in a vessel containing dilute sulphuric acid. These plates were connected to some electric generator, and a current was sent through the cell, which decomposed the electrolyte and oxidized the positive plate. The cell was then discharged; but the energy obtained was very small, since the action was confined to the immediate surface of the plates. But by repeated charging and discharging, first in one direction and then in the other, the oxidation penetrated deeper into both plates, thus increasing the storage capacity of the cell.

Chemical Action in Lead Accumulators. — The exact nature of the chemical changes which occur in lead batteries is not yet fully established. Planté believed the charging action to consist in the formation of peroxide of lead ($Pb\,O_2$) on the positive, and metallic lead (Pb) on the negative, plate, which was converted into lead oxide ($Pb\,O$) on both plates by the discharge. Some authorities still consider this to be the chief, if not the only, action; but it was

* U. S. Patent, Oct. 14, 1879.

shown by Gladstone and Tribe,* and corroborated by subsequent investigations, that the formation of lead sulphate plays an important part.

The probable reaction may be represented as follows: —

CHARGING.

	POSITIVE PLATE.		ELECTROLYTE.		NEGATIVE PLATE.
	PbO_2	$+$	$2\,H_2SO_4$	$+$	Pb
$=$	$PbSO_4$	$+$	$2\,H_2O$	$+$	$PbSO_4$

DISCHARGING.

According to the above equation the active material on both plates is converted into lead sulphate when the battery is discharged. The reasons for believing that this occurs are, first, chemical analysis shows that lead sulphate exists in the discharged plates; second, the density of the solution decreases during discharge, corresponding to the consumption of sulphuric acid and formation of water, as shown by the above reaction; and third, on thermo-chemical grounds, the combination $Pb + O$ does not evolve sufficient energy to account for the *E.M.F.* produced.

"The Chemical Theory of Accumulators" is fully discussed in a series of articles by E. J. Wade; † and "The Chemistry of Secondary Cells" has also been investigated by W. E. Ayrton.‡

ACCUMULATORS OF THE PLANTÉ TYPE.

We have seen that the serious objection to the Planté battery is the great length of time required to form the plates. Planté himself found that previously treating the plates with dilute nitric acid produced an initial oxidation, which hastened the forming process. He also ascertained that mechanically roughening the plates aided the action by increasing their surface and porosity. In his most successful type of cell, the plates consisted of two long, thin sheets of lead rolled up, with strips of cloth interposed to keep them apart. This construction secured very large surface and minimum distance between the plates. Numerous subsequent inventors have devised other forms and arrangements of plates. De Meritens and de Kabath have brought out cells with laminated plates made of very thin ribbons of lead laid or folded together to

* *Nature*, Jan. 5, March 16, July 13, Oct. 13, 1882, and April 19, 1883.

† *Electrician* (Lond.), beginning September, 1894; also *Electricity* (N.Y.), beginning Oct. 10, 1894.

‡ *Journ. Institution of Elec. Eng.*, vol. xix.

give an enormous surface. Montaud covered the plates with a layer of electro-deposited lead, which is quite porous, and readily converted into active material. Lead wire, shavings, and other finely divided forms have been used in accumulators, either by compressing them into plates, or by packing them in perforated tubes of vulcanite or earthenware.

The plates of the Woodward battery are made by pouring molten lead upon common salt. While in a plastic state, the lead and salt are intimately mixed and molded into the proper shape. When set, the salt is dissolved out, leaving a porous plate of lead.

The Crompton-Howell Accumulator is a standard form which is successfully used in England and the United States. It is of the Planté type, the plates being composed of porous crystalline lead, which is afterward formed by repeated charging and discharging. The crystalline lead plates are produced by a peculiar process of casting, the exact details of which are kept secret.

The regular size of plate is about 9 inches square and .4 inch thick; and the various sizes of cell are made by combining a greater or less number of these plates. A large cell for central-station work has 61 plates, contained in a lead-lined wooden trough 4 feet 6 inches long by 12 inches wide and 12 inches deep. The plates are rigidly held apart and supported above the bottom of the vessel, in order to prevent short-circuiting by the accumulation of the material which falls off of the plates. The electrolyte used is a mixture of sulphuric acid and water having a density of about 1.25. This cell can maintain a discharge of 1,000 amperes for 30 minutes, without serious fall of potential.

The Chloride Accumulator is manufactured by the Electric Storage Battery Company of Philadelphia, which combines the Faure, Brush, and several other interests in America. It is also made by English and French companies. This cell is a compromise between the Planté and Brush types.

The manufacture of the chloride accumulator is described in detail in the *Electrical Engineer* (N. Y.) of Dec. 19, 1894, the principal points being as follows: The first step is the production of finely divided lead, which is accomplished by directing a blast of air against a stream of molten lead, the result being a spray of lead which cools and falls as a powder. This is dissolved in nitric acid, and precipitated as lead chloride, by the addition of hydro-

chloric acid. The white chloride thus obtained is washed and dried, and forms the basis of the material which afterwards becomes active in the battery-plates. This lead chloride mixed with a certain proportion of zinc chloride is then melted in crucibles, and cast in molds to form small tablets or pastilles. The latter are square for the negative and round for the positive plates, being about .75 inch in diameter and the same thickness as the plate, and having small holes cast in them, as shown in Fig. 127. These pastilles are then placed in the mold in which the plate

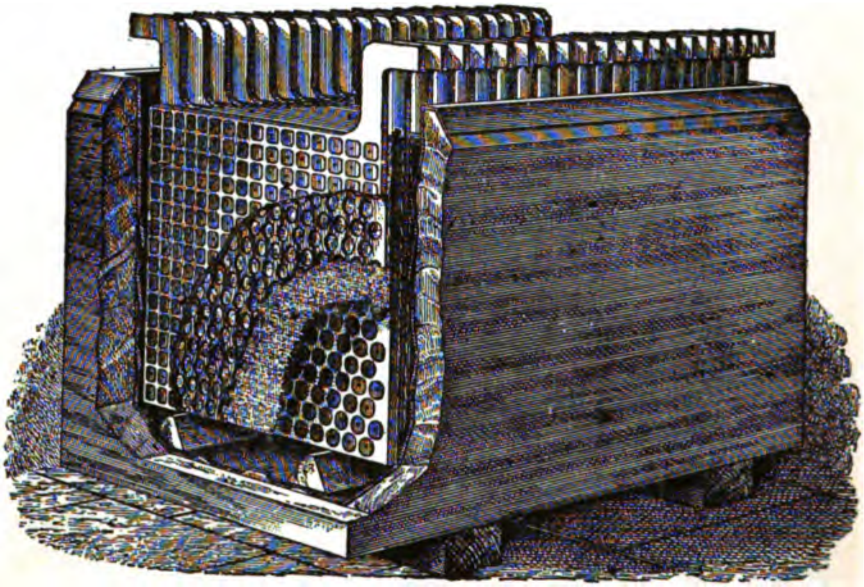

Fig. 127. The Chloride Accumulator.

is cast, being located and held about .2 inch apart by pins projecting through the holes which they contain. Molten lead is then forced into the mold under pressure of 75 lbs. or more per square inch, and completely fills the spaces between the pastilles, producing a solid plate, composed of a grid or frame of metallic lead which firmly holds the pastilles of active material.

The lead chloride in the plates is then reduced by stacking the latter in a tank containing a dilute solution of zinc chloride, slabs of zinc being alternately placed between the lead plates. The plates so assembled constitute a short-circuited primary battery, by which the lead chloride is reduced to metallic lead, the

reaction being $Pb\ Cl_2 + Zn = Zn\ Cl_2 + Pb$. The plates are washed to remove all traces of zinc chloride; and those intended for negatives need no further treatment, since they contain spongy lead. The positive plates, however, require to be formed as follows: The plates, immersed in tanks filled with dilute sulphuric acid, receive a continuous charge of two weeks' duration in one direction, which thoroughly converts the spongy lead into peroxide, the current being furnished by a dynamo.

In setting up the cells, each positive plate is covered on both sides by a sheet of asbestus cloth, as indicated in Fig. 127, and is further separated from the adjacent negative plates by a partition of cherry wood perforated with numerous holes, which are connected by vertical grooves to permit the circulation of the electrolyte and the escape of gases.

The following table gives the data of the various types and sizes of cell. To save space, only the largest and smallest size of each type are given; but in all cases intermediate sizes are made with every odd number of plates. The capacities, weights, etc., of these intermediate sizes are, of course, nearly proportional to the number of plates which they contain.

Data of the Chloride Accumulator.

	Type B.		Type C.		Type D.		Type E.		Type F.		Type G.	
Size of Plate, inches	3 × 3		4 × 4⅝		6 × 6		7¾ × 7¾		10½ × 10½		15½ × 15½	
Number of Plates	3	7	3	7	3	13	5	15	9	19	11	51
Normal Charge or Discharge Rate in Amperes,	.62	1.87	1.25	3.75	2.5	15	10	35	40	90	100	500
Normal Capacity in Ampere Hours	6.25	18.75	12.5	37.5	25	150	100	350	400	900	1,000	5,000
Total Weight of Cell, with Acid and Glass Jar	4	11	7.5	18.5	15	49	34	94	155	295	355	1,552
Length of Cell, inches	2¼	4	2	4	2¼	7¾	3¼	8¾	9	16½	13¾	40½
Width of Cell, inches	4	4	5	5	7¾	7¾	9	9	12½	14½	20½	21½
Height of Cell, inches	4½	4½	6	6	8½	8½	10½	10½	14	16½	24	24

It will be observed that the normal rate of charge or discharge requires ten hours to obtain full capacity. This being too long a time in some cases, an excessive rate of discharge of twice the normal is allowable if desired; but it reduces the useful capacity 20 per cent. On the other hand, a slow discharge rate of one-half the normal increases the capacity 20 per cent.

The smaller sizes are provided with either rubber or glass cells. The larger sizes of type F, and all sizes of type G, have

lead-lined tanks of wood. Cells of greater capacity can be made by the simple addition of plates.

ACCUMULATORS OF THE FAURE TYPE.

At one time batteries of the Faure type, in which the active material is mechanically applied to the plate, were generally used; but the tendency during the last few years has been to revert to the Planté process, or some modification of it in which the active material is formed chemically, or electro-chemically, on the plate.

Nevertheless, accumulators are still manufactured by the Faure method; and they are usually more easily and cheaply made, and have a greater capacity for a given weight, since the proportion of active material is greater. But since the latter is applied as a paste to a lead frame, or grid, it may become loose, so that it fails to make good contact with the grid, or falls off in fragments.

The E. P. S. Accumulator is one of the most prominent of the Faure type, its name being the initials of the Electric Power Sto-

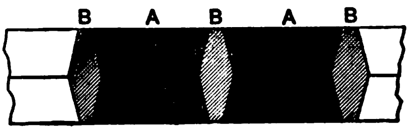

Fig. 128. Cross-section of the E. P. S. Plate.

rage Company, Limited, by which it is manufactured in England. It is also called the Faure-Sellon-Volckmar cell, it being made under the combined patents of these and other inventors. Practically the same battery was manufactured by the Accumulator Company of New York, which for many years carried on the most extensive business in this line in America; but it has now been supplanted by other forms of battery in the United States.

The plate of the E. P. S. cell consists of a lead grid cast in an iron mold, and having the cross-section shown in Fig. 128. The square holes in the grid are completely filled with a paste of red lead or minium ($Pb_3 O_4$) and dilute sulphuric acid for the positive, and litharge ($Pb O$) and dilute sulphuric acid for the negative plates.

The E. P. S. batteries are made in many different sizes and types, of which the L type is a well-known form, being employed

for isolated electric-lighting plants. The data of these cells are as follows:—

E. P. S. Accumulator, L Type.

No. of Plates.	Maximum Normal Charge or Discharge Rate.	Capacity Ampere Hours.	Approximate External Dimensions.			Weight, Complete with Acid.
			Length.	Width.	Height.	Wooden Cell.
7	13 amperes	130	5¼ in.	13¼ in. for	18 in. for	74 lbs.
11	22	220	8	wooden	wooden	107
15	30	330	9¼	and 12	and 13¼	143
23	46	500	14¼	for glass	for	228
31	60	660	19	cell.	glass cell.	286

The total weight with the glass cells is about 8 per cent less. One of the more recent forms of E. P. S. cell is the K pattern, which is arranged in very compact form, the volume and weight per ampere of discharge being only about one-half as great as in the older types.

The Tudor Accumulator is very largely used on the continent of Europe, and has recently been introduced in this country. The plate is made of lead, with fine grooves extending over nearly the entire surface. These are filled with the ordinary paste of lead oxide. The action of the cell further increases the amount of active material by oxidizing the lead plate, the surface of which is very great by reason of the numerous grooves. This cell is therefore made according to both the Faure and Planté processes.

Tudor Cells.

Type.	Available Capacity Ampere-Hours.	Maximum Current in Amperes.		Dimensions of Cells in Centimeters.			Total. Weight.
		Charge.	Discharge.	Length.	Width.	Height.	Kgms.
I.	26	6	8	12	21	35	10
V.	91	21	28	30	21	35	30
X.	270	54	72	42	42	55	110
XIV.	630	126	168	74	42	55	230

In addition to those given above, all of the intermediate sizes between I. and XIV. are made.

A battery of larger cells is in use in the Head Place Station of the Edison Company of Boston, Mass., a description of which is given in the *Electrical Engineer* (N.Y.) of Sept. 18, 1895. The plant contains two batteries of 72 cells each. Each cell consists of a lead-lined wooden box, 3 feet 10 inches long, 3 feet 4

inches wide, and 3 feet deep, in which are suspended 18 positive and 19 negative frames. Each positive frame is composed of 16 plates 7 inches square; while each negative frame has 4 plates 14 inches square, thus giving an enormous surface in each cell. The plates are secured in their respective frames by lead strips. The frames are held in position about one-half inch apart by vertical glass tubes, and rest upon thick glass plates placed on edge in the bottom of the cell, the frames being thus raised 6 inches above the floor of the cell. It is said that these two batteries combined are capable of supplying 6,600 amperes at 110 volts for 1¼ hours, which would usually cover the period of very heavy load. This is an output of 726 kilowatts, or nearly 1,000 horsepower for 1¼ hours, being a remarkably high discharge rate.

The Tudor accumulator is now manufactured in the United States by the Electric Storage Battery Company of Philadelphia, who also make the Chloride battery.

It is recommended for central-station use, particularly where the rate of discharge is great, as, for example, when the total time of discharge is only 1½ to 4 hours. For this work the negative plates are of the Chloride type, the positives being the heavy Tudor plates described above.

Lithanode. — Mr. Desmond Fitzgerald has made plates for accumulators by compressing the active material itself into a solid mass instead of applying it to or forming it upon a plate of metallic lead. The plates thus produced are known as lithanode; their advantages being the elimination of the dead weight of the lead plate, and the reduction of local action by reason of the fact that lithanode is more homogeneous than plates containing metallic lead. Lithanode is only useful for the positive plates, the ordinary grid or other form being employed for the negatives. Dr. Frankland has also utilized lithanode in his accumulators.

Accumulators containing Metals Other than Lead. — It was stated in the beginning of this chapter that almost any primary cell would act more or less perfectly as a secondary cell; as, for example, the common gravity battery. A great many accumulators have been devised in which the lead in one or both of the plates has been replaced by some other metal. For example, Reynier made the negative plate of zinc instead of lead; this zinc in discharging being converted into zinc sulphate, which

dissolved in the electrolyte. The substitution of zinc for lead secures an increase in initial *E.M.F.* from 2.2 to 2.5 volts, and also allows of a considerable reduction in weight; since for the storage of a given amount of energy the weight of zinc required is much less than that of the equivalent lead. A difficulty with this type of cell is the formation of "trees" of zinc on the negative plate during the charging process, which are likely to fall off or extend across to the positive plate, thus short-circuiting the cell. Another difficulty is the difference in density of the solution between the top and bottom of the plates, the tendency being to exhaust the zinc sulphate from the upper portion of the liquid during charging, and to produce too dense a solution at the bottom during discharging. It has been attempted to avoid this trouble by arranging the plates horizontally, so that the density would be uniform for each plate; but the difficulty then arises that the gases which form to a certain extent in almost all batteries collect between the plates, and interfere with the chemical action and the passage of the current.

A similar type of cell has been manufactured by the Union Electric Company of New York, in which the negative plates consist of thin sheet copper covered with an amalgam of zinc, and the positive plates are made up of laminæ of lead held together by leaden rivets, and perforated with numerous small holes, these positives being formed by the Planté process.

Waddell-Entz Accumulator. — The copper-alkali-zinc primary battery of Lalande and Chaperon, being reversible in action, can be used as an accumulator. Waddell and Entz have constructed accumulators on this principle. In this cell when discharged the positive plate consists of porous copper; the electrolyte is a solution of potassium zincate, and the negative plate is composed of sheet iron or gauze. When the cell is charged, the electrolyte is decomposed, metallic zinc being deposited on the negative plate, the porous copper of the positive plate is oxidized, and the liquid becomes converted into a solution of caustic potash (potassium hydrate).

This accumulator has been used with considerable success for traction purposes; but its *E.M.F.* is so low, being only about .7 volt, that it would require 170 to 180 cells for the ordinary 110 volt electric-lighting circuits, allowing for loss of potential in the

battery and conductors. This number is three times as great as is required with the lead accumulator, and is a serious objection to any low-voltage cells.

The lead-zinc, the zinc-alkali-copper, and other similar types, are often called bimetallic accumulators, to distinguish them from the simple lead battery; but there are other kinds of cell which contain only a single metal.

For example, a very simple accumulator * consists of two electrodes of carbon and a solution of zinc bromide. During charging, the latter is decomposed, metallic zinc being deposited upon one electrode, and bromine, which is set free at the other plate, is dissolved in the liquid. The reaction is thus $ZnBr_2 = Zn + Br_2$. This cell is interesting on account of its simplicity, the action consisting solely in the separation and combination of two chemical elements; and it is also important because the theoretical weight of active material ($ZnBr_2$) required is less than 4 lbs. per horse-power hour, whereas the corresponding materials in a lead battery weigh about 25 lbs. The practical trouble with this cell is the difficulty of keeping the bromine away from the zinc. If a thick, porous diaphragm is used for this purpose, it offers too much electrical resistance. This cell shows, however, possibilities of the great desideratum of the electrical engineer, — a light-weight accumulator.

MANAGEMENT OF ACCUMULATORS.

In describing the application and handling of accumulators, the ordinary lead batteries of the Planté and Faure types will be considered, as they constitute a large majority of the cells in use.

Setting up the Cells. — The battery is usually placed on the floor, or upon strong wooden shelves, of which Fig. 130 shows one form adapted to cells of medium size. Iron stands are sometimes used for large and heavy batteries, but they must be protected from the acid fumes and drip by acid-proof paint. Wooden stands should be varnished or treated with parafin for the same reason. It is very important to have every cell accessible for inspection, cleaning, and renewal, it being desirable to be able to reach both sides of the cells; and there should also be ample space between the shelves to lift out the elements.

* C. S. Bradley, U. S. Patent of Feb. 24, 1885.

It is highly important that the cells should be thoroughly insulated from each other, in order to avoid leakage of current. This is accomplished by standing each cell on four oil-insulators of glass or porcelain, as represented in Figs. 129 and 130. Glass cells are often set in wooden trays filled with sand or sawdust, to distribute the strains and absorb the drip.

It is well to use glazed brick or tiles for the walls and floor of the room containing an accumulator, in order that they may be easily washed. Wooden floors are quickly rotted by the acid.

In connecting the cells, which are usually put in series, great care should be observed to join the terminals positive to negative, and so on. The positive poles are usually painted red, or otherwise distinguished. It may be noted at this point that the nomenclature concerning accumulators is different from that of primary

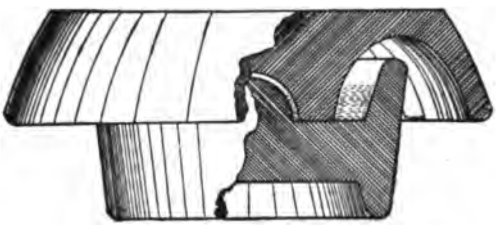

Fig. 129. Oil Insulator for Battery.

batteries. The positive plate in the former is the peroxide plate, and the one from which the current flows out in discharging, whereas that would be the negative plate in a primary cell. The positive pole or terminal in an accumulator is an extension of the positive plate, and is connected to the positive terminal of the dynamo in charging; consequently there is really much less cause for confusion than there is with the primary battery.

It is well to actually test the polarity of each cell and of the circuit before making connections, which may be done with any of the forms of pole-tester, or by the simple expedient of dipping the two terminals in dilute acid, the one from which the most bubbles (hydrogen) arise being negative. The connections should be scraped thoroughly clean, and screwed up very tight, as they are particularly exposed to corrosion.

The Electrolyte. — Practice varies considerably in regard to the proper strength of solution to use. Ordinarily sulphuric acid

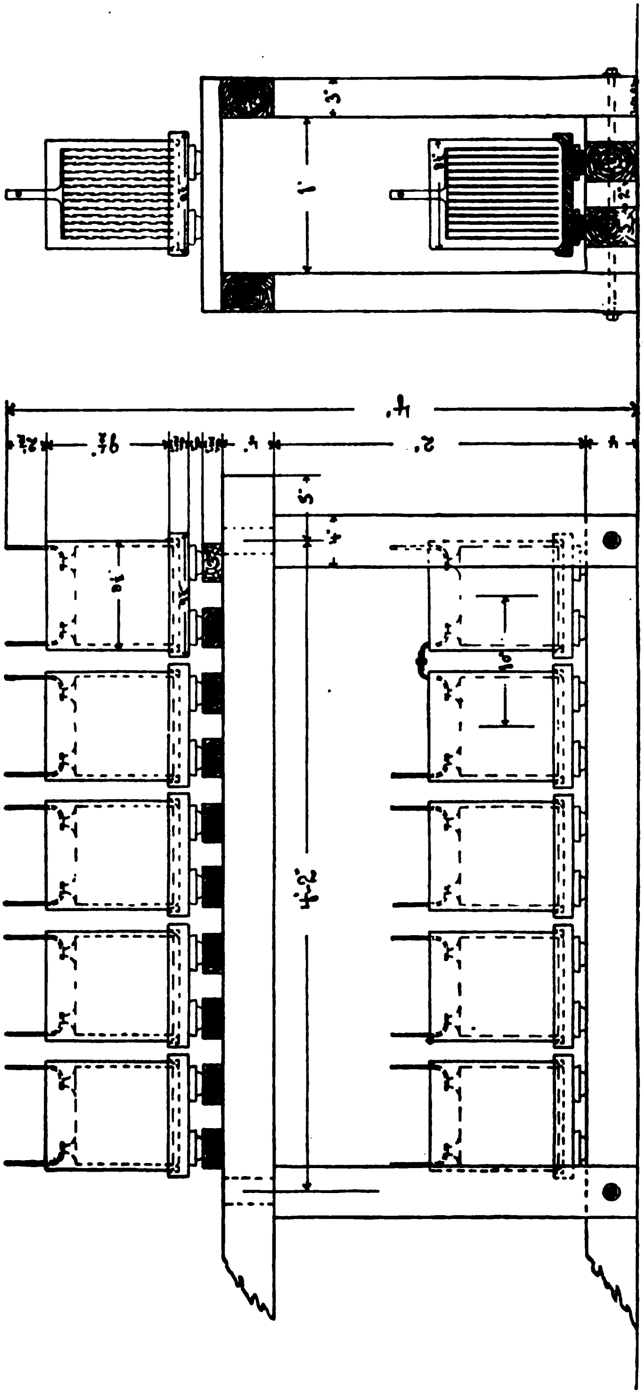

Fig. 130 Wooden Battery Stand.

is poured into water until the density becomes about 1.2, and the cells are filled with this mixture.* Sometimes a density as high as 1.25, or even more, is used. The advantage of a strong solution is its lower resistance; but it is liable to produce the very objectionable effect of "sulphating," which will be considered later. The density of the electrolyte falls immediately after filling a cell, since some of the acid is taken up; but it rises again in charging, for example, from 1.20 to 1.25. It is convenient to keep a hydrometer in each cell to observe the density of the liquid, not only in the beginning, but as a permanent indicator of the amount of charge and general working condition.

The effects of the electrolyte upon the action of accumulators has been investigated by H. A. Earle.†

Charging. — The charging should begin immediately after a new cell is filled with liquid, otherwise the plates are likely to become sulphated; but this depends upon the type and condition of the cell. The first charge differs in some respects from subsequent regular charging; it being desirable to begin slowly, and continue steadily for a long period of time. For example, we may use one-half the normal current, and continue for twice the ordinary time.

The following are the ways by which the amount of charge in a battery may be ascertained: —

Indications of Amount of Charge in an Accumulator. — 1. The *E.M.F.* rises from 1.9 volts, which is the minimum value to which a lead battery should be discharged, to 2.4, or even 2.5 volts, when very fully charged. The rise is quite gradual, but is more rapid near the beginning and end of the charge, as shown in Fig. 131. The external voltage is higher in charging than in discharging because of the internal resistance. (See pages 378 and 379.)

2. If an account is kept of the exact number of ampere hours of charge and discharge, the actual amount of energy in the battery at any time is known, due allowance being made for leakage of current and other losses. For this purpose any integrating instrument, such as Thomson's recording meter, may be used.

3. The density of the electrolyte gradually rises during the

* Water should never be poured into sulphuric acid, as it is likely to cause some of the liquor to be thrown out violently.

† Paper before British Association meeting, Sept. 16, 1895. *Electrical Review* (Lond.), Sept., 1895.

charging operation, the density when charged being about .05 higher than when discharged.

4. Bubbles of gas are given off freely when the battery is fully charged, since the plates are then no longer able to take up the oxygen and hydrogen which tend to be set free by the electrolysis. These bubbles give the electrolyte the appearance of boiling; and often they are so fine that the liquid looks almost milky white, particularly in a cell which has not been very long in use.

5. The color of the positive plates varies from a reddish brown to nearly black when fully charged; and the negatives change from a pale to a darker slate color, but they are always lighter in color than the positives. This last indication of the amount of charge is only acquired by experience, but is quite definite after one becomes familiar with a particular battery.

The proper rate of charging depends upon the size and type of cell, and is usually specified by the manufacturer in each case, since it is merely an empirical fact. An excessive rate of charging may injure the plates, and very slow charging is a waste of time, except with a new or disabled battery.

The current for charging is ordinarily obtained from a direct current dynamo; but any other direct current source, such as a primary or thermo-electric battery, may be employed. The potential required for charging must exceed that of the battery, which then acts as a counter *E.M.F.*, the expression being $C = \frac{P - e}{R}$, in which C is the current, P the potential applied to the battery, e the counter *E.M.F.*, and R the internal resistance of the battery. Usually P is about 5 or 10 per cent greater than e, in order to produce the necessary current C through the resistance R; but in practice P is regulated until the proper current C is obtained. The above equation, put in the form $R = \frac{P - e}{C}$, enables the internal resistance R to be calculated; but since it varies considerably with the temperature and with different amounts of charge, its exact value is not often considered. Another form of the above expression, viz., $e = P - CR$, shows that the true *E.M.F.* of the battery is less than the charging voltage applied to it by an amount equal to the product of the charging current and the internal

resistance. Conversely, in discharging, the total *E.M.F.* of the battery is greater than the difference of potential p between its terminals by the same amount, that is, $e = p + CR$.

Hence it is necessary to know C and R, or to measure the voltage when the circuit is open (in which case $C = 0$), in order to find the real *E.M.F.* This applies to each individual cell as well as to the entire battery, and is important in determining the amount of charge or working condition of a particular cell.

If the charging voltage P be kept constant, it is evident from the first of the above equations that the current C will gradually decrease, since e, the counter *E.M.F.* of the battery, steadily rises, as shown in Fig. 131, which represents the voltage of a Chloride

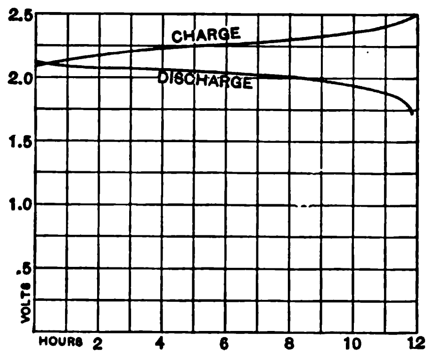

Fig. 131. Variation of E. M. F.

accumulator during charging and discharging. This effect is counteracted somewhat by the fact that the internal resistance R also diminishes, owing to the increased density of the electrolyte. This gradual reduction in the strength of the charging current is considered very desirable by some authorities, since it enables the battery to take a greater charge than if the current were maintained at full strength. On the other hand, this "tapering charge" makes it difficult to keep account of the exact number of ampere hours supplied to the battery; and in ordinary commercial work it is often considered simpler to charge with a constant current.

The charging operation may be continued until the battery is fully charged, as shown by the indications stated above; since most types of cell are not injured even by overcharging at a moderate rate, in fact they are often benefited by it, for it elimi-

nates injurious "sulphating." It would not be wise, however, to overcharge an accumulator often, since it might cause the plates to disintegrate or buckle, and it would also be wasteful of current.

Discharging. — An accumulator is in most cases discharged within a few hours after being charged, as, for example, in electric lighting, when the engine and dynamo are run during the day for charging the battery which supplies current to the lamps during the night. But a portable accumulator for feeding lamps might be required to retain its charge for several days. A certain loss of charge occurs in any battery, and this increases with the length of time that it is kept charged. This leakage is not very serious, however, if the interval between the charge and discharge is not over twelve hours, which is about the limit in ordinary practice.

The operation of discharging is naturally the converse of charging; and the changes which have been described as occurring in the latter take place also in the former, only in the reverse order. The normal rate of discharging is usually about equal to that of charging, but may, perhaps, be a little greater. An excessive discharge rate is injurious to most types of accumulator, since it may disintegrate the plate, or abnormally heat the electrolyte. The paste may be driven out of the grid of a Faure cell; but it is claimed for the plates formed by the Planté type that they are not even injured by being short-circuited, which would produce the maximum current and discharge them very rapidly. But in any case a short circuit or excessive current is very undesirable; and a battery, like a dynamo, should be protected by a fuse or preferably by an automatic circuit-breaker or overload switch (page 397).

An accumulator should never be discharged completely, as it is very likely to become "sulphated," or otherwise injured; and, moreover, the *E.M.F.* falls so rapidly toward the end of the discharge, that the current would be of no practical value. The limit of discharge is usually considered to be the point at which the *E.M.F.* drops to 1.9 volts.

The charge which is thus left in an accumulator is usually about 25 per cent of the total capacity; but it involves no considerable loss of energy or efficiency, since it remains in the battery each time, and the charging begins at that point.

The Efficiency of Accumulators. — The efficiency of any apparatus is the ratio between that which it consumes and that which

it gives out. While this seems extremely simple and definite, there are several opportunities for confusion or quibble when it is applied to a secondary battery.

In the first place, the "ampere efficiency," which is the current in ampere-hours gotten out of the battery, divided by the ampere-hours that are put into it, is quite different from the *watt efficiency.* The latter is the real efficiency; since it considers the *energy,* and includes the voltage as well as the ampere-hours. Ampere efficiency may be scientifically interesting as showing the action of a battery; but it has little commercial importance, and is unfortunately used, either from ignorance or intention, to give a false idea of the merit of accumulators, since the ampere efficiency is often 10 or 12 per cent higher than the watt efficiency. We have only to consider the ampere efficiency of an alternating-current transformer supplied with 1,000 volts and 10 amperes, and producing about 100 volts and 100 amperes, to realize the danger of laying much stress on ampere efficiency. The cases are not exactly parallel, but in both the failure to consider voltage leads to useless results.

Another difficulty in this connection is the fact that it is possible to obtain an apparent efficiency of over 100 per cent from an accumulator. Since a certain amount of charge is left in the cell, it is possible to apparently draw more ampere-hours of current out of it than are put in, by simply discharging it more than usual. This matter has been investigated by Ayrton,* who states that: "If an E.P.S. accumulator be over and over again carried around the cycle of being charged up to 2.4 volts, and discharged down to 1.8 per cell, the charging and discharging currents being the maximum allowed by the makers, viz., .026 ampere per square inch in charging, and .029 ampere per square inch in discharging, the *working efficiency* thus obtained may be 97 per cent for the ampere hours, and 87 per cent for the watt hours. If, on the contrary, the cell be constantly charged up before being tested, then for the first few charges and discharges between the above limits, and with the same current density in charging and discharging, even the *energy* efficiency may be as high as 93 per cent; whereas, if the accumulator has been left for some

* "The Working Efficiency of Secondary Cells," *Journal of the Institution of Electrical Engineers*, vol. xix.

weeks, then, although it was left charged, the energy efficiency for the first few charges and discharges will be as low as 70 per cent."

Considering the actual efficiency obtained in regular working as being the only figure of any practical importance, we find that Professor Kennedy* gives 91.2 per cent ampere efficiency, and 82.1 watt efficiency, as being the result of regular commercial operation at the Westminster Station in London. The Chloride accumulator is claimed by its makers to have 96.7 per cent ampere and 84.9 per cent watt efficiency. Similar figures are given by other reputable authorities. Even admitting these values to be true, they show a loss of energy which is high for electrical apparatus, being twice as great as that in a good dynamo or motor, and about five times as large as the loss in the best alternating-current transformers. As a matter of fact, however, it is doubtful if even these figures can be realized except under favorable conditions. In the description of the accumulator plant of the Edison Electric Illuminating Company of Boston, already referred to,† it is stated that the records show that "the batteries have only 75 per cent efficiency." It is probable that this is a fair figure in ordinary commercial work; and it is only in plants where the amount and rate of discharge are below the full capacity, or perhaps under the stimulating influence of a test, that higher efficiencies are obtained.

Depreciation of Accumulators. — The depreciation is often claimed to be as low as 10, or even 5, per cent per year. The reference cited above states that the Tudor battery in the Edison Station in Boston is insured and kept in repair by its makers for 4 per cent per annum of its original cost. This figure is about as low as the maintenance of the best steam or electrical machinery. On the other hand, the life of accumulators in traction or train-lighting work has not been over one year in many instances; or, in other words, the depreciation was at least 100 per cent. Even in stationary use, when not exposed to the jarring and severe conditions existing on cars, batteries often deteriorate very rapidly, and a large fraction of the plates have to be renewed each year. Improvements in the manufacture and care of accumulators have

* *Electrical Review* (N.Y.), July 15, 1893.

† *Electrical Engineer* (N.Y.), Sept. 18, 1895, p. 271.

undoubtedly resulted in greatly reducing their depreciation. One must be somewhat guarded, however, in accepting low figures, since from their nature accumulators are very easily injured and difficult to repair. Nor should it be forgotten that most types of battery have only been in use for a few years, and it is obviously absurd to predicate the deterioration of the eighth or tenth year upon that of the second or even fifth year. Nothing but actual experience can possibly determine such a question. A depreciation of 2 per cent during the first year may grow to 20 per cent during the eighth year; and this increase may be quite sudden.

It would probably be very unwise for any one purchasing a battery without the makers' guaranty to allow less than 10 per cent depreciation per annum; and this does not include interest, taxes, or other charges. It is also a fact that such a guaranty is rarely carried out, because some change of conditions or complete alteration of plant relieves the manufacturer from responsibility.

REMEDY OF TROUBLES IN CONNECTION WITH ACCUMULATORS.

The most serious troubles which occur in accumulators are *sulphating*, *buckling*, and *disintegration* of the plates. These can usually be avoided or cured if they have not gone too far, by proper treatment. But the management of accumulators may demand even more experience and care than the handling of machinery, because the chemical actions which occur in the former are more difficult to determine and correct than most mechanical actions, the latter being usually far more definite and tangible.

Sulphating. — The normal chemical reactions which take place in accumulators are supposed to produce lead sulphate ($Pb\,SO_4$) on both plates when they are discharged, their color being usually gray or brown. But under certain circumstances a whitish scale forms on the plates, probably consisting of a sulphate having the composition $Pb_2\,SO_5$. Plates thus coated are said to be "sulphated." This term is, therefore, somewhat ambiguous, since the formation of ordinary lead sulphate ($Pb\,SO_4$) is perfectly legitimate, but the word has acquired a special significance in this connection. A plate is inactive, and practically incapable of being charged, where it is covered with this white sulphate.

The conditions under which this objectionable sulphating is likely to occur are as follows: —

a. If an accumulator is over-discharged, i.e., run below the limits of voltage specified under the head of discharging.

b. When an accumulator is left discharged for some time, even if these limits have not been exceeded.

c. If the electrolyte is too strong.

A battery may be over-discharged, or may remain discharged a long time because of leakage of the current by defective insulation of the cells or circuits, and the plates may be short-circuited by particles of active material or other substance falling between them. Plates which have become very badly sulphated through accident or carelessness are almost beyond recovery, and there is little to be done but exchange them for new plates. A moderate amount of sulphate may be removed by carefully scraping the plates. The faulty cells should then be charged at a low rate — about one-half of the normal — for a long period of time. In this way, by fully charging and only partially discharging the cells for a number of times, the unhealthy sulphate is gradually eliminated. When the plates are only slightly sulphated, the latter treatment alone is sufficient without any scraping.

Adding to the electrolyte a small quantity of sodium sulphate or sodium carbonate, which latter is immediately converted into sodium sulphate, tends to hasten the cure of sulphated plates, probably by dissolving off the deposit. In practice, however, this remedy is not usually employed; and, when it is, the cells should be emptied and refilled with the ordinary electrolyte, after they have been brought back to proper condition.

Sulphating not only reduces the capacity of lead accumulators, but also tends to use up the material of the plates by forming a scale which falls off, or has to be removed. It also tends to produce the following trouble: —

Buckling, or warping of a plate, is caused by the action not being uniform on the two surfaces. For example, a patch of white sulphate on one side of a plate will prevent the action from taking place there, so that the expansion and contraction of the active material on the other side, which occur in normal working, will cause the plate to buckle. This might be so serious that it would be impossible to straighten the plate without breaking or

cracking it; but, if taken in time, it may be accomplished by placing the warped plate between boards, and subjecting it to pressure in a screw or lever press. Pounding the plate is objectionable, because it cracks or loosens the active material; but, if it be necessary to straighten a plate in this way, a wooden mallet should be used very carefully, with flat boards laid under and over the plate. Buckling may be caused by an excessive rate of charging or discharging, as well as by sulphating.

Disintegration. — Some of the material may become loosened or entirely separated from the plates, as a result of various causes. The chief one of these is sulphating, which forms scales or blisters that are likely to fall off, thus gradually reducing the amount of active material and the capacity of the cell. Buckling also tends to disintegrate the plates. Contraction and expansion of the active material take place in normal working, and are increased by excessive rates or limits of charging and discharging. This constitutes another likely cause of disintegration, particularly in plates of the Faure type containing plugs or pellets of lead paste. The fragments which fall off of the plates not only involve a loss of material, but are also liable to extend across or gather between the plates, and cause a short circuit.

The positive plates are far more susceptible to and injured by these troubles than the negatives. The former are also more expensive to make, therefore it is to them that special attention should be directed in the management of storage batteries.

Troubles from Acid Spray. — An accumulator gives off occasional bubbles of gas at almost any time or condition, but when nearly charged the evolution of gas becomes more rapid. These bubbles, as they break at the surface, throw minute particles of acid into the air, forming a fine spray which floats about. This spray not only corrodes the metallic connections and fittings in the battery room, but is also very irritating to the throat and lungs, producing an extremely disagreeable cough.

Glass covers are sometimes placed over the cells to prevent the escape of the fumes. A layer of oil upon the surface of the electrolyte is also used to stop the formation of the spray, and at the same time to prevent the evaporation of the liquid. The presence of oil, however, interferes with the use of hydrometers or other apparatus for determining the density of the electrolyte.

A plan which consists in spreading a layer of granulated cork over the surface of the liquid in the cell is free from the last-named objection, since the particles of cork may be temporarily brushed aside from the stem of the hydrometer. Both of these methods of arresting the spray have the effect or appearance of making the cell dirty, and the former has the objection that the plates may become coated with oil if they are lifted out. It is, therefore, customary to rely almost wholly upon ventilation to get rid of the acid fumes. They may also be neutralized by producing ammonia vapor in the battery room. Metallic articles should be protected by coating them with acid-proof paint, varnish, or vaseline.

CHAPTER XXI.

APPLICATIONS OF ACCUMULATORS IN ELECTRIC LIGHTING.

THE function of accumulators is to receive electrical energy at one time or place, and to give it out at some other time or place.

The principal uses to which they may be put in electric lighting are the following: —

1. To supply portable electric lamps.
2. To take up fluctuations, and thus steady the voltage or current.
3. To furnish energy during certain hours of the day or night, and enable the machinery to be stopped.
4. To aid the generating-plant in carrying the heavier load which usually exists for only an hour or two.
5. To make the load on the engines more uniform by charging the battery when the load is light.
6. To transform from a higher to a lower potential by charging the cells in series, and discharging them in parallel, or *vice versa.*
7. To subdivide the voltage, and enable a three- or a five-wire system to be operated with a single dynamo.
8. To supply current from local centers or sub-stations.

Each of these applications will be considered separately in the above order.

1. **Portable Accumulators.** — The accumulator is practically the only means of supplying portable electric lamps, or those which are not connected to a dynamo, even if they are stationary.

The primary battery is expensive and troublesome to operate; and it has never been commercially successful for electric lighting, except where only a few small lamps are required. Nor is there any other satisfactory primary source of electrical energy except the dynamo driven by mechanical power, as already explained in Chapter VII. It is therefore practically essential to adopt accumulators wherever portable electric lamps are used.

The various manufacturers furnish portable forms of accumulator; for example, the Chloride battery is arranged in a strong wooden box provided with handles, as shown in Fig. 132. The usual number of cells is from 1 to 5, giving from 2 to 10 volts; and the sizes of plates are types "C," "D," and "E," the data of which have already been given on page 369. The jars are of rubber, being sealed to prevent the spilling of the liquid.

The serious objection to portable accumulators is their great

Fig. 132. Portable Accumulator.

weight. For example, a standard size which weighs 100 pounds yields 10 volts and 5 amperes, or 50 watts, for 10 hours, which is just sufficient to feed one ordinary incandescent lamp of 16 candle-power. This weight would be prohibitive in most cases, in which the only way to carry the battery was by hand; but it might be allowable for lighting railroad trains, where the weight would not be so objectionable.

Their great weight would also discourage in most instances the use of accumulators for supplying lamps in places which are not connected to a generating-plant, the batteries being carried back

and forth from a charging station. This method might be resorted to on special occasions, such as a *fête*, to which ordinary commercial limitations do not apply; but for regular lighting it would be both troublesome and expensive.

Small accumulators are used to feed miniature lamps for medical or dental purposes, in which case their weight is not a serious difficulty in view of the importance of the work, and the small amount of energy required. Small batteries are also employed for theatrical lighting effects, in which the lamps and batteries are carried by the performers when it is not convenient to supply the current by a wire connection.

2. **Accumulators for preventing fluctuations,** due to unsteadiness in the driving-power, are often applied successfully. A dynamo driven by a gas-engine, for example, may vary periodically in speed because of the explosive action of the gas in the cylinder; and a battery connected in parallel with the dynamo will have the effect of steadying the voltage. But in the discussion of the gas-engine on page 201, it was pointed out that improvements in design and construction tend to reduce unsteadiness of speed; and, by the use of a heavy fly-wheel and an elastic connection between the engine and dynamo the result is sufficiently satisfactory in most cases to make a battery unnecessary. An accumulator is generally installed in connection with a small gas-engine lighting plant to enable the engine to be stopped for a considerable portion of the time, and thus save labor and attention, in which case the battery may also act to prevent fluctuations; but its principal function is the former one, which will be considered next.

A windmill electric-lighting plant absolutely requires, as already stated on page 222, an accumulator or some other means of storing energy, not only to eliminate fluctuations in speed which are constantly occurring, but also to bridge over the considerable periods of calm weather.

3. **Accumulators to enable machinery to be stopped during certain portions of the day or night.** — The advantage of this application depends upon the fact that, in almost every electric-lighting plant, there are long periods during the day and late at night when the number of lamps lighted is so small that it may not pay to run the generating machinery.

For example, Fig. 133 is a load diagram showing the combined

output of all the London stations on Dec. 20, 1894. The maximum load was 11,600 kilowatts at 5.30 P.M., and the minimum, 800 kilowatts at 4 A.M. The average load was about 4,000 kilowatts, which is about one-third of the maximum; that is, the load factor was 33 per cent. The load factor during the summer would be less, since the nights are shorter. In fact, the form of the load curve depends upon the season, the number of lamps, classes of customers, latitude of station, and other conditions. With a load diagram of the form shown, the generating-plant might be run from 2 P.M. until midnight, during portions of which time the accumulators are charged; for example, from 2 to 4 and from 8 to 12 o'clock; after midnight the machinery is stopped,

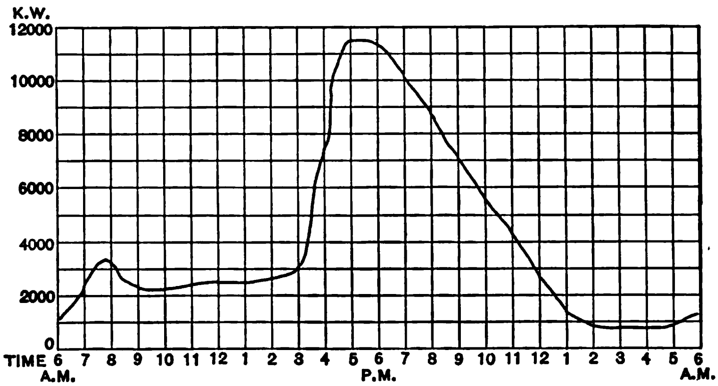

Fig. 133. Combined Load Diagram of London Stations.

and the current is supplied by the battery until the dynamos start again at 2 o'clock the next afternoon, and so on. This enables one set of employees, working 10 hours a day, to operate the plant, very little labor being required by the battery during the remaining 14 hours.

This plan also allows the machines to rest and cool down, which greatly facilitates cleaning and repair. In a hotel, residence, or on board of a yacht, it may also be very desirable to stop the machinery, and avoid the vibration and noise during the night. On the other hand, the addition of an accumulator to an electrical plant renders the latter heterogeneous, since the battery and its management differ so radically from the machinery and the handling of the same. It must also be remembered that the total invest-

ment is increased by the cost of the battery and its accommodation, because the generating-plant is perfectly able to carry the load put upon the battery, since, by hypothesis, this load is a light one. Hence the machinery might be run all the time; in which case the battery would be entirely unnecessary, and sufficient rest of the machinery could be secured by using different machines for the periods of light load on successive days. These statements are based upon the supposition that the battery is not used to help the dynamos at the time of maximum load, since this case will now be considered separately.

4. **Accumulators to aid in carrying the Maximum Load.** — Assume, in the case of the load diagram shown, that the generating machinery is capable of supplying 8,000 kilowatts, and that an accumulator is used to furnish the remaining 3,600 kilowatts at the time of maximum load, that is, the "peak" of the load diagram. This simply means that batteries are substituted for a certain portion of the machinery plant, and the question is whether the substitution secures any advantage.

The first cost of a battery for a given rate of output simply depends upon the time of discharge. Most accumulators have a normal period of discharge of about 10 hours, at which rate the price of accumulators to furnish a given number of watts would be 3 to 5 times as great as that of the equivalent boilers, engines, and dynamos combined. But if the time of discharge is reduced to about 2 or 3 hours, the costs are about equal, and with a still higher rate the cost of batteries would be less. For example, Mr. C. L. Edgar * states that he has installed a Tudor accumulator, costing $50,000, which has the same output of about 750 kilowatts, as a machinery plant costing $64,000. It should be noted, however, that the battery is discharged at a higher rate than that for which it was guaranteed, and that the price given for the machinery assumes the very best triple-expansion engines, etc., whereas Mr. Edgar said, in the same discussion, that cheap machinery could be used to carry the "peak" of the load, since it lasts for such a short time that efficiency is not very important.

The ultimate effect of rapid discharge on the life of the plates depends upon their construction, the frequency with which they are subjected to this strain, and upon other conditions; but it

* *Trans. Amer. Inst. Elec. Eng.*, Nov., 1895.

would undoubtedly be injurious in any case. As stated on page 382, it is impossible to determine the average depreciation for ten or twenty years from an experience of two or three years.

The capacity of an accumulator is always reduced by quick discharge. For example, the catalogue of the Chloride battery shows that the output is 16 per cent less at twice the normal rate. The efficiency is also lowered, but not to the same extent.

Hence it appears that batteries are not very well adapted to the rapid discharge required to carry the maximum load, and that it would hardly be wise to install them instead of machinery for this purpose alone. This would be particularly true if the latter consisted of gas-engines, which are more efficient than steam-engines, and involve much smaller losses in starting up and standing idle.

5. **Accumulators to Maintain Uniform Load on the Engines.** — Steam-engines are very inefficient at light loads, as already explained on page 189. This inefficiency, in fact, is one of the chief sources of loss in an electric-lighting plant; and the principal object of the engineer who designs and operates a station should be to reduce this waste to a minimum. The accumulator is the most important means of accomplishing this result, although there are other methods, such as gas, thermal (hot water), and steam storage, all of which have been carefully compared by Mr. Nelson W. Perry.* Judicious selection of the number and sizes of the engines would enable them to be worked at a considerable fraction of their full capacity nearly all of the time, and it would seem that the same care that would be required to manage the battery might enable this to be accomplished. Nevertheless, the accumulator gives more flexibility to the plant; and, where introduced, it often seems to considerably increase the economy of the engines by making their load more uniform, and nearer to their full capacity. According to the figures given by Mr. Perry in the paper cited above, an electrical horse-power costs $48.68 per annum when developed steadily, and costs $117.78 per annum with a variable load similar to that of an electric-light station; that is, the latter costs about 2.4 times as much as the former. This ratio seems

* Paper before the National Electric Light Association, February, 1895, on "Storage of Energy Essential to Economy of Working Central Stations."

very high, but is borne out by statistics,* which give a very large coal consumption for most electric-light stations.

Under these circumstances, almost any method of making the engine loads more uniform should increase the economy of working. Doubtless an accumulator would benefit any plant in which an engine runs for a considerable portion of the time at less than half of its full power.

If a plant is so small that it contains only one engine, it may be necessary to run it a great deal of the time far below its full load. But even with two engines, it is generally possible to select the sizes so that the smaller one runs economically during the periods of light load, the larger one alone is suited to medium loads, and both are used for the maximum output, the times during which any engine is very much underloaded being very short. With a greater number of units, it becomes still easier to properly apportion the load; and when there are five or more engines, as is usually the case in large stations, the loss from this cause should be trifling. To be sure, the waste of energy which occurs from using boilers for variable loads still remains; but, according to the figures given by Mr. Perry, this is less than that due to the engines, and general experience shows this to be true. There is also some steam used in heating up the engine each time that it is started, or to keep it warm when not running; but in most cases the loss thus involved would not be a large item.

6. **Accumulators Used as Transformers.** — If the cells of a battery are arranged in series while being charged, and in parallel for discharging, a high-voltage current will be required for charging, and a low-voltage current will be given out. The total amounts of energy measured in watts are the same, less the loss of 15 or 20 per cent which always occurs in accumulators. The result is similar to that obtained by an alternating-current transformer or motor-dynamo. Such a method of transformation of potential might be employed in connection with long-distance transmission of energy, the current being sent over the line at high voltage, and converted to low voltage by accumulators for local distribution. For potentials of several thousand volts, which are commonly employed in transmitting long distances, the num-

* See Report of Committee on Data to National Electric Light Association. *Electrical World*, March 2, 1895, p. 273.

ber of cells required would be so great as to make this of doubtful practicability compared with the ordinary stationary or rotary transformers, but it would give uniformity in load and other advantages which may be secured by the storage of energy.

7. **Accumulators Used for Subdividing Voltage.** — This application is similar in principle to the preceding. The most important practical case is that in which a dynamo of 220 volts charges a battery of corresponding potential, a three-wire system being supplied from the battery, the neutral wire of which is connected to the middle point of the battery, as represented in Fig. 134. This arrangement avoids the necessity of running two dynamos, and allows the battery to be placed in a sub-station near the districts to be supplied, so that it is only necessary to run two conductors to that point instead of three. The same principle may be applied to the five-wire system.

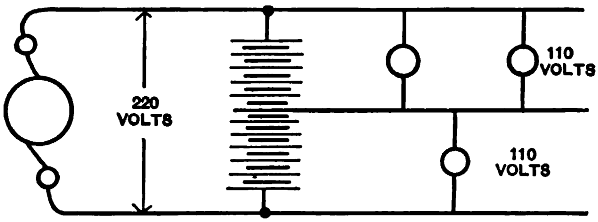

Fig. 134. Voltage Subdivided by Accumulator.

8. **Accumulator Sub-stations.** — The plan of installing battery plants at local centers, which are charged from the main station, enables some of the conductors to be saved in a three- or five-wire system, as already stated. It also makes it possible to reduce the size of these conductors, because the current which flows over them can be kept practically constant, so that it is not necessary to have them large enough to carry the maximum current consumed by the lamps, which may be several times the average value. This also gives the same steady load on the generating machinery as if the battery were located near it.

The batteries at the various sub-stations may be connected and charged in series or in parallel. The former plan would require far less copper in the conductors; since the voltage is multiplied by the number of batteries in series, and the current is the same as for a single battery. On the other hand, this high

difference of potential would exist between the first and the last batteries of the series; and if either of these became grounded, any person connected to the earth and touching a wire supplied by the other battery would receive a shock due to the total voltage. This would demand that the maximum difference of potential should not exceed 500 volts; or, in other words, four batteries of 110 to 125 volts each might be charged in series, and could be connected to the lamp circuits at the same time. This would practically amount to a five-wire system using accumulators to subdivide the potential, explained on page 394. If the batteries were entirely disconnected from the lamp circuits while being charged, the latter would be free from danger of the high pressure, which might therefore be 1,000 or 2,000 volts if desired, the batteries being charged during the day and supplying the lamps at night. For continuous working, two batteries would be necessary with high voltage; but the one used to carry the light load could be much smaller than the other. Accumulator sub-stations not only save copper in the feeders, but also reduce the cost of, and lost voltage in, the distributing conductors, because the batteries can be placed near the lamps to be supplied with current.

Accumulators Used for Two or More of the Above-named Purposes. — Each of the different uses of the storage battery has been considered separately to avoid the confusion with which this subject is often beset; but, as a matter of fact, the employment of the accumulator for several of these purposes is the most common practice. By thus combining these different applications the plant may be rendered not only more economical, but also much more flexible. For example, the battery may be utilized to help out the generating machinery at times of heavy load, or when the latter is partially or wholly disabled. It often happens that it is difficult to produce or maintain sufficient steam-pressure, owing to poor draught or other circumstances, in which event a battery enables the boilers to be temporarily relieved of some or all of the drain upon them while the pressure is being raised to the proper point. It may also be necessary or desirable to shut down the machinery, or a portion of it, for a few minutes to make some repair, adjustment, or change of arrangement, connection, etc.

It is also possible to feed some of the circuits from the battery, while the others may be supplied at a higher or lower voltage by

the machinery. In these and many other ways an accumulator may be a very convenient adjunct to an electric-lighting system. The fact that it is so radically different from the machinery in its nature and action makes it very unlikely that the entire plant will be crippled at any one time, since the two sources of current are not exposed to the same dangers. An accident to the steam-piping, for instance, might shut down all of the machinery, but it probably would not affect the battery; and, *vice versa*, an accident to the latter is not likely to extend to the former.

In many special cases there is absolutely no doubt of the advantage of an accumulator. A factory or store might require a few lamps burning all night, and it would certainly be cheaper to supply these from a battery than to run a dynamo. The economy secured by the use of "Storage Batteries in Office Buildings" is set forth by Mr. Charles Blizard.* This is an excellent example of a service for which they are particularly adapted; the load being very heavy between four and six o'clock in the afternoon, and quite light during the rest of the time, and at night only a few lamps are lighted.

Connection and Regulation of Accumulators. — The complete control of a battery in an electric-lighting plant requires provision to be made for feeding the lamps from either the dynamo or battery separately, or from the two working in parallel; and it should be possible to charge the battery at the same time that lamps are being supplied. This requires three switches, — one to connect the battery to the dynamo, one to connect the lamps to the dynamo, and one to connect the lamps to the battery. In some plants the second switch is omitted, because the lamps are always fed by the battery alone, the latter being charged during the day, when no lamps are in use. It would seem, however, desirable to have all three switches in every plant in order to be able, at least, to supply lamps and charge the battery at any time.

There should be an amperemeter in the battery circuit having a scale on both sides of zero, so that it shows whether the battery is being charged or discharged, as well as the value of the current. Another similar amperemeter is required in the circuit between the dynamo and the battery, to show the direction and amount of current. A third amperemeter is desirable in the lamp cir-

* *Electrical Engineer* (N.Y.), Nov. 6, 1895.

cuit, to show the total current supplied to them; but it need only indicate on one side of zero, since the current there always flows in the same direction. A voltmeter is required with a three-way switch, which enables it to be connected to the dynamo, battery, or lamps respectively.

An *overload switch* must be inserted in the battery circuit. This acts automatically to open or introduce resistance into the circuit when the current becomes excessive, being analogous in function to the ordinary fuse. An *automatic cut-out* is required between the dynamo and the battery to open the circuit when the charging current falls below a certain value, and thus avoid any danger of the battery discharging through the dynamo, if from any cause the *E.M.F.* of the latter drops below that of the former. This completes the ordinary measuring and circuit-controlling apparatus employed in connection with accumulators. This arrangement is shown diagrammatically in Fig. 136, in which *A* and *A* are the two amperemeters, the third one being omitted in this case; *V* is the voltmeter; *E*, voltmeter switch to connect to the dynamo, battery, or lamps as desired; *G*, busbars; *L*, lamps; *D*, dynamo; *R*, rheostat in field-circuit of dynamo; *S*, switch, battery to lamps; *S*,′ switch, dynamo to battery; *S*″, switch, dynamo to lamps direct; *O*, overload switch; *C*, automatic cut-out; *K* is the battery, and *HH* are the reserve-cell switches for regulation. Fig. 135 shows the switchboard on which these devices are mounted.

The Regulation of Accumulators is one of the most troublesome matters involved in their practical use. This arises from the fact that their voltage falls continually from the beginning to the end of their discharge. To be sure, this decline is perfectly gradual; but its total value is large, being from about 2.2 to about 1.9 volts, which is a decrease of nearly 14 per cent.

In order to maintain a constant voltage, the usual plan is to have a number of extra cells, which are successively switched into the circuit as the potential falls. These reserve cells and the switches which control them are represented at H H in Fig. 136. The contact pieces of these switches must be made in such a way that they do not short-circuit the cells as they pass from one point to the next. This is accomplished by splitting the movable contact arm into two parts, between which a certain amount of

resistance is introduced, so that when the two parts happen to rest on two adjacent contact points, the resistance prevents the cell which is connected to these two points from being short-circuited, and also avoids breaking the circuit.

The number of extra cells required depends upon the conditions in each case, but if the lamps demand 110 volts, it would require 51 cells to obtain 112.2 volts when the cells are fully charged, and give 2.2 volts each, assuming the load to be so light that the loss

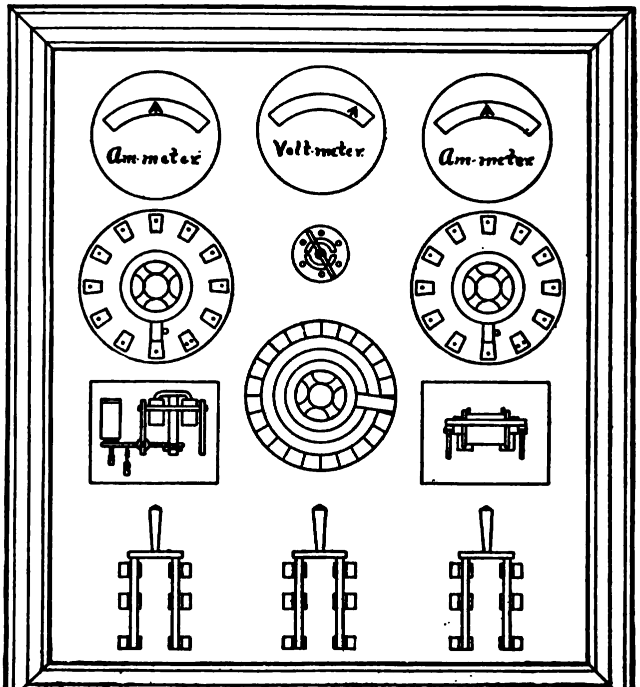

Fig. 135. Switch-board for Accumulator Plant.

of pressure on the conductors is only 2 per cent. When the battery becomes discharged, and its potential falls to 1.9 volts per element, 8 additional cells, or 59 in all, would be needed. These would yield 112.9 volts, assuming the average potential of the reserve cells to be 2 volts, since they have not been discharged to the same extent as the original battery. At maximum load the drop on the conductors will probably be at least 10 per cent of the lamp voltage, so that the potential at the battery will have to be

$110 + 11 = 121$. This will necessitate 4 more elements, or a total of 63 when the 51 original cells are fully discharged to 1.9 volts, and the 12 extra cells give 2 volts each. If the drop were 15 volts, the necessary number of cells would be 65.

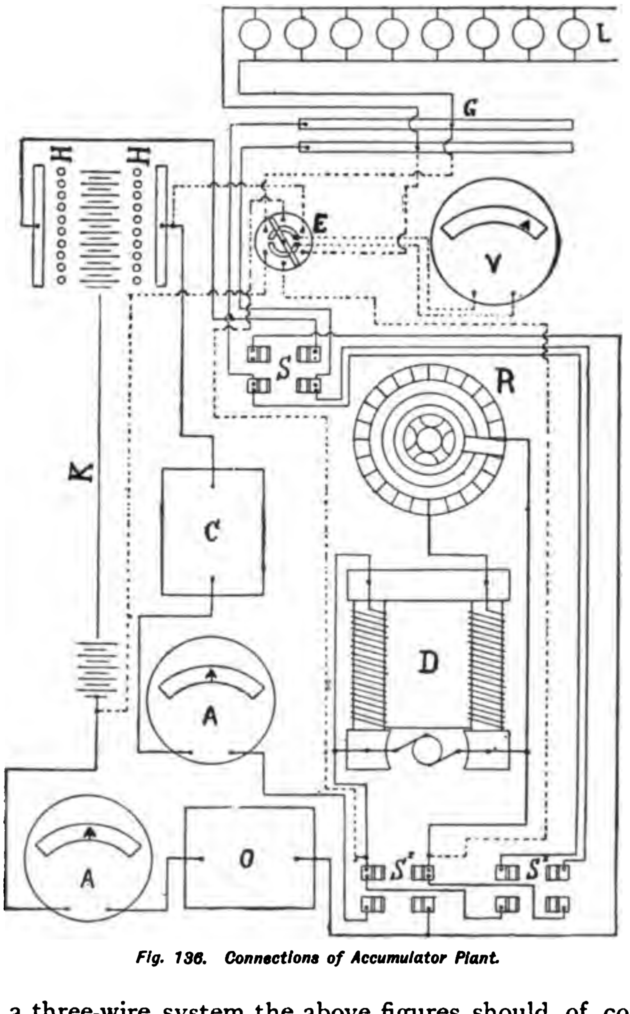

Fig. 136. Connections of Accumulator Plant.

For a three-wire system the above figures should, of course, be doubled. This switching of extra cells into and out of the circuit obviously results in discharging them unequally, hence they require to be charged to a corresponding extent. This is accomplished by successively cutting the cells out of circuit as soon as they become

fully charged, the last cell which was put into the circuit being fully charged in the shortest time, and so on. The amount of charge is determined by the methods given in the preceding chapter. If cells are employed which are not injured by overcharging, they may be left in circuit until the entire battery is fully charged. This saves the trouble of periodically operating the switch; but it is wasteful of energy, since the full counter *E.M.F.* and resistance of the charged cells must be overcome, which requires the dynamo to generate about 2.5 volts more per element.

The switching apparatus used for controlling the cells in the Boston Edison Station is described in the *Electrical World*, Dec. 14, 1895.

Automatic Regulation. — The operation of the reserve cell switches may be made automatic in discharging. This requires a device which causes the switch arm to move to the next point and add another cell each time the voltage falls one volt below the normal, thus raising it again one volt above its average value. For example, a voltmeter pointer may be arranged to close a circuit and operate an electromagnet which moves the switch through a step-by-step action. Such devices as these, however, are not usually very reliable, owing to failure to make good contact and difficulty of keeping them in adjustment. Furthermore, a difference of one or two per cent in potential is hardly sufficient to produce a definite effect. The hysteresis of an iron core, for example, would more than offset this slight change in magnetizing force. In a central station or large plant it would usually be far better to operate the switches by hand than to depend upon any such automatic regulation.

The automatic switching off of the extra cells in charging would be done with reference to the voltage of the individual elements, and not of the battery as a whole; but ordinarily this plan is not any more desirable than automatic regulation in discharging. Another method consists in automatically operating the reserve-cell switch at certain times by means of clockwork; for example, a new cell might be cut in at the end of each hour, or at intervals corresponding with the rate of discharge. This assumes that the load diagram is about the same every day; and in many cases this might be sufficiently true to give fair regulation. This device would certainly be more positive and

reliable in its action than one operated by very small variations in voltage. The clockwork could be set differently according to the season of the year or other conditions.

In place of using reserve cells to maintain a constant potential during the discharge of an accumulator, it is possible to employ resistance coils or counter *E.M.F.* cells, which are gradually cut out of circuit as the *E.M.F.* falls. This allows all of the accumulator cells to be kept in circuit, and charged and discharged equally; which greatly reduces the attention required to manage the battery, and would be a decided advantage in a small plant. The plan, however, involves waste of energy in dead resistance or counter *E.M.F.*; but this would not amount to very much in a small installation. Another objection to the introduction of resistance into the circuit is the variation in voltage which it occasions, with changes in the current strength. A resistance of .1 ohm, for example, causes a drop of 2 volts when the current is 20 amperes; but if it increases to 100 amperes, owing to the turning on of more lamps, the drop would then become 10 volts, and the effective potential would fall 8 volts, which would greatly diminish the light of the lamps. Consequently it would be necessary to regulate the rheostat, not only for the gradually decreasing *E.M.F.* of the battery, but also for any variation in the current.

This last difficulty can be avoided by using counter *E.M.F.* cells in place of resistance coils. These consist of simple lead plates or grids without active material, and immersed in dilute sulphuric acid of about 1.1 density. The counter *E.M.F.* set up by these cells is practically constant, and independent of the value of the current. Their internal resistance being very low, the drop due to it is small; hence they produce an almost constant reduction in the voltage of a battery, with which they are connected in series in order to bring down its potential during the first part of the discharge. They are cut out one by one as the *E.M.F.* of the battery falls, thus keeping up the effective pressure.

Regulation of Dynamos in Connection with Accumulators. — The variation in *E.M.F.* which occurs in accumulators renders it somewhat difficult to regulate the dynamos employed to charge them. It has already been stated in the last chapter that a constant

potential applied to a battery will give a decreasing rate of charge, owing to the gradual rise in its counter *E.M.F.* This is advantageous, in that it enables the cells to receive a larger charge. But the increase in their voltage is so great that it is practically necessary to regulate the dynamo a certain amount; and in practice it is customary to maintain the charging current approximately constant for considerable periods of time, otherwise it would be difficult to determine the quantity of energy put into the battery, and its efficiency. When extra cells are used they facilitate the regulation of the dynamo, since they are gradually cut out as the charging progresses and the *E.M.F.* rises.

If the lamps are supplied at the same time that the battery is being charged, some provision must be made for the fact that it may be necessary for the voltage of the dynamo to be considerably higher than that required by the lamps. One plan is to have two switches *H* and *H* connected to the reserve cells, as shown in Fig. 136, the charging current from the dynamo being led in through one, and the current for the lamps passing out through the other, so that the potential can be independently controlled in the two circuits. Another method is to insert counter *E.M.F.* cells (without active material) in the circuit between the dynamo and the lamps, in order to bring down the voltage of the former to suit the latter. The number of these cells is varied in accordance with the excess of the potential of the dynamo.

Simple resistance coils may be used in place of the counter *E.M.F.* cells to reduce the pressure; but the cells have the great advantage, already stated, that they have an effect practically independent of variations in the current. All of these methods, however, involve a waste of power, the value of which in watts is the product of the current in amperes, and the number of volts by which the potential is cut down. In small plants this loss is not serious, but in large plants or central stations it may become very considerable.

The best way to overcome this trouble is to make use of an auxiliary dynamo or "booster;" in which case the main dynamos are run at the proper voltage to supply the lamps directly, and the additional potential required to charge the battery is furnished by the booster. This is connected in series with the dynamo, being inserted in the circuit between the latter and the battery.

By this plan only the power actually required is generated, and the consumption of energy by counter *E.M.F* or dead resistance is avoided.

The reserve cells employed for regulating the voltage enable several circuits to be supplied with different potentials. For example, the longer feeders of an electric-lighting system may be operated at higher voltage to make up for their greater drop in pressure. This is accomplished by including a greater number of cells in circuit with such feeders by means of the reserve-cell switches already described.

A very complete discussion on "Storage Battery Applications" took place at the New York, Chicago, and San Francisco meetings of the American Institute of Electrical Engineers, Nov. 20, 1895.* Most of the other important papers and articles on the subject have been referred to in this chapter and the preceding one. The principal books treating of accumulators may be found in the list below.

Recherches sur L'Électricité, by Gaston Planté, Paris, 1883.

The Storage of Electric Energy, a translation of the above by P. B. Elwell, London, 1887.

The Chemistry of Secondary Batteries, by Gladstone and Tribe, London, 1883.

Piles Électriques et Accumulateurs, by Émile Reynier, Paris, 1884.

The Voltaic Accumulator, a translation of the above by J. A. Berly, London, 1889.

Traité des Piles Électriques, by D. Tommasi, Paris, 1889.

Secondary Batteries, by J. T. Niblett, London, 1892.

The Voltaic Cell, by Park Benjamin, New York, 1893.

Electric Light Installations, vol. i., Management of Accumulators, by Sir D. Salomons, Seventh Edition, London, 1894.

* *Transactions*, vol. xii.

CHAPTER XXII.

SWITCHBOARDS, INCLUDING SWITCHES, FUSES, AND CIRCUIT-BREAKERS.

VARIOUS electrical conductors and apparatus, such as switches, measuring instruments, and other auxiliary devices, are required to connect and control the different dynamos and circuits in an electric-lighting plant. These might be considered to be mere details of the system, but they constitute a branch of the subject which is by no means insignificant.

Station Conductors. — Electrical conductors which connect the dynamos with the switchboard, and other conductors in the dynamo-room, may be arranged according to three different plans: —

1. They may run overhead as aërial lines.
2. They may be carried along the walls or ceiling.
3. They may be laid under the floor.

All three of these plans are commonly used, and the preference would depend upon circumstances.

1. *Overhead station conductors* possess the advantages of cheapness, shortness of path, and accessibility for inspection and repair; any short-circuit or ground could be instantly seen and removed, whereas it might occasion great uncertainty and delay in the case of conductors placed under the floor.

Overhead conductors in the dynamo-room may consist of rods of copper of circular or rectangular cross-section, and may be bare, provided the potential is not over 300 volts. In the case of high-tension conductors of 1,000 volts or more, they should be covered with insulating material, to prevent accidental contact with persons, or with wires or other conductors which might fall across or touch them. These conductors, whether insulated or bare, are supported by suitable rods or brackets. One of the simplest and neatest arrangements consists of an iron or brass

pipe, screwed into a flange or socket in the ceiling, and provided with a ring or strap at its lower end, which is lined with an insulating bushing of porcelain or hard rubber, through which the conductor passes.

2. *Conductors laid along the walls or ceiling* are similar in character and arrangement to those just described, and are often more easily supported; a simple porcelain insulator attached to the wall being usually sufficient, and applicable alike to high- or low-tension conductors. Low-potential wires may be laid in molding or interior conduits, similar to ordinary house-wiring; but in the station it is often desirable to have the main conductors visible and accessible, even though they may be somewhat unsightly, and this last objection can be largely avoided by neat arrangement.

3. *Conductors laid under the floor* have the advantage over either of the preceding plans that the wires are entirely out of the way; and this is an especially important matter in large plants, where an overhead traveling crane is almost a necessity for handling the dynamos and other machinery. Overhead conductors, or even those carried to the side walls, are decidedly in the way of a traveling crane, and interfere seriously with the great convenience which it affords in handling heavy machines or parts.

The placing of the wires under the floor also gives a clearer and neater appearance to the station. They have the disadvantage of inaccessibility already mentioned, and also the liability of becoming wet when the floor is washed. The first difficulty is overcome by providing a specially made trough or conduit in the floor, the cover of which is flush with the latter, and is made in convenient lengths to be easily taken up for examining or repairing the conductors. Wires under the floor should have a first-class moisture-proof insulating covering, so that they would not be short-circuited or grounded, even if submerged in water.

In case there is another story or space below the dynamo-room, the conductors can be run down through the floor, and carried along below on porcelain insulators, like the ceiling conductors already mentioned.

Since so much depends upon the perfect insulation and continuity of these conductors, the greatest care should be exercised in laying them, so that they are a sufficient distance apart at all points, and do not run too near any gas- or water-pipe, iron beam,

brick or stone walls, or other body which might ground or otherwise injure them. Where it is necessary for them to pass through a wall, partition, or floor, they should be insulated with a tube of porcelain or other suitable material.

All conductors, including those which connect the dynamos with the switchboard, as well as the 'bus bars or wires used for connecting the various switches, instruments, etc., should be of ample size to be free from overheating and excessive loss of voltage. It is not uncommon to find a drop in pressure of two per cent or more between the generators and the switchboard. This should be reduced to one, and preferably to one-half, per cent, because it interferes with the proper regulation of the apparatus, and adds to the less easily unavoided drop on the distributing conductors.

This subject belongs more properly under electrical distribution; but it may be stated as a general rule that these conductors should have a cross-section of at least one square inch per 1,000 amperes.

Switchboards. — In many of the early electric-lighting plants the switchboards were made entirely of wood; but so much trouble was caused by fire and short-circuits, that some non-combustible material is now considered almost essential. One of the best of these is marble; since it is a good insulator, is not hygroscopic, has a fine appearance, is not affected by any reasonable temperature, and can be obtained free from conducting veins, the last named being, in the case of slate switchboards, a source of great trouble. Slate has been extensively used for switchboards; and where it can be obtained free from the conducting veins just mentioned, it is an excellent material, since it is considerably stronger and tougher than marble. It is often "marbleized;" that is, treated in such a way as to fill the pores, and thus prevent the absorption of moisture, and at the same time make an imitation marble, which it is almost impossible to distinguish from the real.

Switchboards composed of glass plates or earthenware tiles have also been used with good results, white glazed tiles being particularly well suited to this purpose. Wood should not be used for a switchboard, except, possibly, where the switches, fuse-blocks, supports for wires, etc., are all of porcelain, or other incombustible substance, so that the wood, in the form of slats,

is merely a frame or backing to which these various devices are attached, all parts of the circuit being kept away from the wood, so that there is no danger of touching or burning it. Since marble, slate, tiles, or glass plates are not convenient to use in sizes larger than one or two feet square, it is necessary to make up large switchboards of many panels, which are held together by frames of iron, brass, or wood. The presence of a metal frame is, of course, objectionable, since it may cause short circuits; but it is customary to employ it, since it is a simple way to support the slabs of insulating material. Wooden frames have been substituted for metallic ones, the idea being that the switchboard itself is made of incombustible material, and the wooden framing merely holds it together.

The arrangement of instruments, switches, connections, etc., on a switchboard, should be conveniently and systematically carried out. The path of the current should be as short as possible, and preferably always in one direction; that is to say, it may pass from left to right, or from top to bottom, or *vice versa,* the wires being brought in on one side, and carried out on the other. The crossing of wires or connections is to be avoided as far as possible.

Wires, and all parts carrying current, should be placed far enough apart at all points to prevent accidental contact, or the jumping across of the current where the difference of potential is great. Wires and current-carrying parts must also be kept at a sufficient distance from conducting bodies, such as screw-heads, metal brackets, gas-pipes, etc., to avoid accidental grounds or short circuits. Instruments and switches should be accessible for observation and operation; but, at the same time, parts carrying high-voltage currents must, if possible, be placed out of reach of accidental contact by persons, or else protected by an insulating shield.

There are three important classes of switchboards used in electric lighting: —

1. Low-potential incandescent lighting at about 110 or 220 volts.
2. Series arc lighting at 2,000 to 7,500 volts.
3. Alternating-current switchboards for 1,000 to 2,500 volts.

An example of the first class is shown in Fig. 137, and a form for use in connection with a storage battery is illustrated in Fig. 135. The description of this and the other types will be given in Volume II., it being necessary to study the systems of distribution, regulation, etc., in order to understand the complete switchboard.

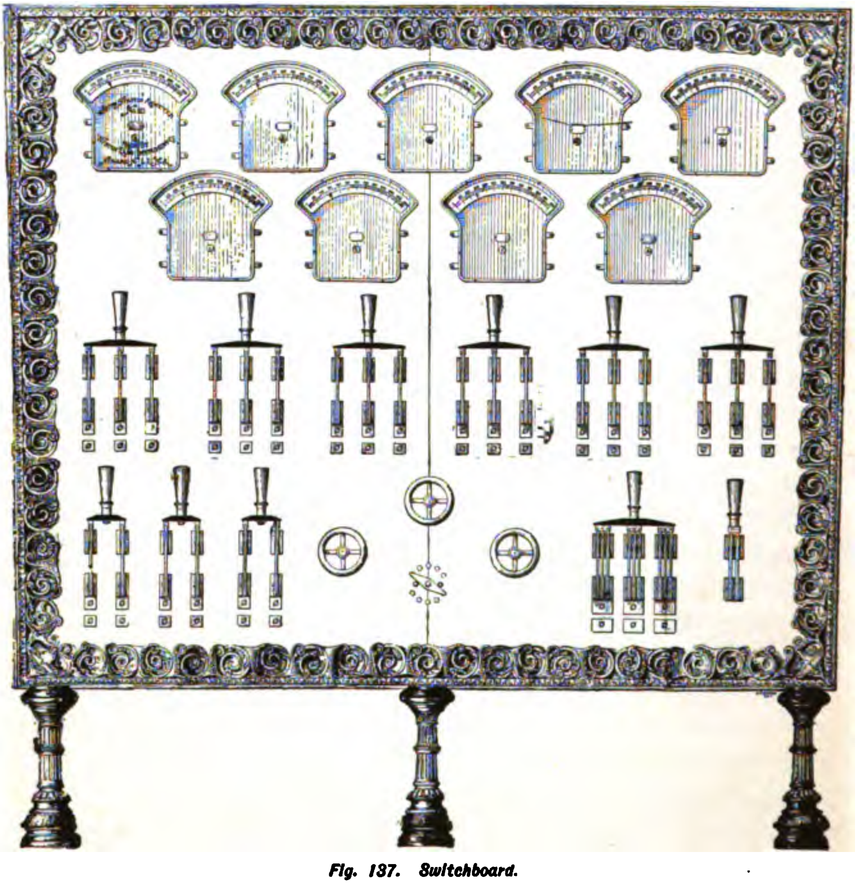

Fig. 137. Switchboard.

Switches are devices for closing and opening the various circuits or branches. The *base* of a switch is made of slate, marble, or other fireproof material. In good practice, wood is no longer allowable for switch-bases. If, however, in an emergency it must be used, as, for example, when a marble switch-base has become cracked, it should be protected by a sheet of mica or

asbestus, to prevent charring of the wood. The base of a switch requires to be very strong in order not to break, crack, or bend, on account of the mechanical strains and the heating effect of arcs, both of which are quite severe in the case of large switches.

The contact surfaces of switches should be ample, the minimum area being .01 square inch per ampere; and in the case of arc-light or other high-voltage circuits where the current is usually small, the contact surface should be .02 to .05 square inch per ampere. The surfaces should have a *sliding contact;* a simple normal pressure between two surfaces being entirely unsatisfactory for the purpose, as the least dirt or oxidation would prevent good contact. In this country some of the well-known forms of "knife" switches are almost universally employed to control large currents, that is, those exceeding 10 or 20 amperes; but in Europe, switches are often used in which the contact is made by the ends of a number of strips of copper bent into semicircular form. This form of switch insures even better contact than the knife switch; but the objection to it is that the ends of the separate strips of copper dig into the contact surfaces and roughen them.

In the knife switch the blade enters between two copper springs or clips, which are pressed together, the blade often being made somewhat loose in order to adjust itself; in fact, perfect alignment and fit of the blade and the clips are somewhat difficult to accomplish, and is the chief trouble with this form of switch. Hence, to insure a good contact, particularly if the blade cannot adjust itself, the springs should be made flexible either by building them up of several thicknesses of metal, or by slitting them into a number of separate fingers. The contact pieces should be shaped so that they open along their entire length at the same time, otherwise the arc formed would concentrate at the last point or corner of contact, and thus burn or melt it away. Indeed, the arc produced by opening a circuit carrying a heavy current is one of the most difficult matters to control in practical electrical engineering; but ordinarily in electric lighting, circuits are not opened while a heavy current is flowing. In case of accident, however, it might be necessary to do this; and a switch should be capable of opening the circuit with full current a reasonable number of times without serious injury.

But if a circuit has to be opened very frequently, some of the forms of circuit-breaker, that are described at the end of this chapter, should be adopted.

In "quick-break" switches the contact-pieces are snapped apart by spring action, the object being to make the time during which the arc exists as short as possible. These are useful in many cases; but the most recent practice, particularly in large plants, is to employ circuit-breakers for interrupting currents of any considerable volume, either automatically or by hand. Simple knife switches are also provided; but their function is to close, rather than to open, circuits, and to make connections that are not likely to be broken while large currents are flowing.

All parts of a switch which carry current should have a cross-section of at least one square inch per thousand amperes for copper, and two or three times as much for brass. It is not uncommon to find switches in which brass pieces used to convey current become highly heated at full load. This, of course, is extremely objectionable, and probably arises from the mistake of making the brass conductors of the size that would be right for copper, whereas the former only has about one-third the conductivity. As far as possible, copper should be used for the current-carrying parts of switches and other portions of the circuit; and if brass is adopted because it is easier to work, or presents a more ornamental appearance, its lower conductivity must always be taken into account. In designing switches, the current should not be allowed to pass through springs which act mechanically, that is, those which are not mere contact springs; since the heat of the current is almost certain to "kill," or take the elasticity out of them. To avoid this, one or both ends of the spring may be insulated. The current should not be allowed to pass through any pivot, bearing, or fulcrum, as the contact is uncertain, and the current is likely to melt the parts together and prevent the movement of the switch. In small switches this rule is often violated, but in good practice the blade or arm itself should extend from one contact point to the other. The screws for holding the conductors should be large enough to stand being firmly tightened; iron screws with square or hectagonal heads are preferable to brass or slotted screws in the case of conductors of any considerable size. The effective length of the screws ought to be at

least twice their diameter to avoid stripping the thread; in short, considerable strength is required to hold the conductors firmly in place. Some device should be provided to hold the switch open and prevent accidental closing. This can usually be accomplished by simply placing the switch so that the arm hangs downward by gravity when it is open. The stupid mistake is often made of reversing this arrangement, so that the handle tends to fall and close the switch; which danger should be avoided, even if the switch is provided with a catch to hold it open. The handle of any switch, even for low-tension currents, must always be perfectly insulated. Special forms of switches for arc, alternating, and other circuits will be described under Electrical Distribution in Volume II.

Safety Fuses. — Almost all electrical circuits, except those for constant-current arc-lighting, are protected from abnormal increase of current by safety fuses. These consist of wires or strips of metal introduced into the circuit, and so designed in cross-section and resistance that they will melt and open the circuit in case of excessive current, before the rest of the circuit becomes unduly heated. These devices are extremely simple, and would seem to be very satisfactory for the purpose; nevertheless, much uncertainty exists in regard to the theory and practice of safety fuses.

The requirements for an effective safety fuse may be stated as follows: —

1. They should melt with a definite current.
2. They should not change in this respect by the effect of time, heating, or other action of the current, or in fact under any reasonable conditions.
3. They should act promptly.
4. They should give a firm and lasting contact with the terminals to which they are attached.

The ordinary practice is to manufacture spools or coils of wire, composed of some easily fusible alloy; or, for larger currents, flat strips of fusible metal provided with copper terminals are used. The idea is that each size of fuse will carry a certain normal current, but will melt and open the circuit with a certain excess of current, which is usually put at 25 per cent or $33\frac{1}{3}$ per cent increase. But, as a matter of fact, the fusing point is consider-

ably modified by many conditions, such as temperature of the surrounding air, position of the fuse, whether it be open or enclosed, vertical or horizontal, and whether it be on the floor, wall, or ceiling. The length of the fuse has also a great effect, the heat being rapidly absorbed from the ends of a short fuse by the blocks to which it is connected; and, furthermore, the size of these pieces would vary the amount of heat which they are capable of taking up.

It is evident, therefore, that the exact conditions under which a given fuse is to be used should be specified, in order to secure uniform results. In fact, fuse blocks or boxes should be standardized, in which cases they ought to be sufficiently reliable in their action, since the physical principles upon which they depend are simple and definite. Their construction is also so very simple and cheap that it would seem to be a mistake to give them up for more complicated devices, except in certain cases. The objection is often urged against fuses that they have a certain capacity for heat which allows the current to rise considerably above the normal point if it increases very suddenly. This is actually an advantage, because the conductors and apparatus which the fuse protects have a still greater heat capacity; consequently a momentary excess of current which does not melt the fuse cannot cause any injury in the rest of the circuit. This avoids the interruption of the supply and the renewal of the fuse every time there happens to be a rush of current for an instant.

A paper and discussion on "The Rating and Behavior of Fuse Wires," by Professor W. M. Stine and others, contains valuable information upon this subject.*

A report by Mr. W. McDevitt to the Philadelphia Board of Fire Underwriters on "The Gross Untrustworthiness of Fuse Metals and Appliances as a Means of Protection for Electric Circuits — The Remedy," † gives the results of many tests on fuses. It is a question, however, whether the difficulties are not largely or entirely due to improper and variable conditions, that can be avoided as already pointed out.

Electromagnetic Circuit-Breakers, cut-outs, or limit-switches are used in place of fuses to protect electrical circuits from exces-

* *Trans. Amer. Inst. Elec. Eng.*, October, 1895.

† *Electrical Engineer* (N.Y.), Feb. 5, 1896.

sive current. The circuit leads through a helix, as represented in Fig. 138, the electromagnetic action of which automatically opens a switch when the current reaches a certain strength. The final break occurs on the carbon strips on each side, thus saving the metallic switch-contacts from the destructive flashing which takes place when heavy currents are interrupted. Circuit-breakers possess the advantages over fuses that they can be instantly opened by hand if desired, they are easily closed and put in condition to

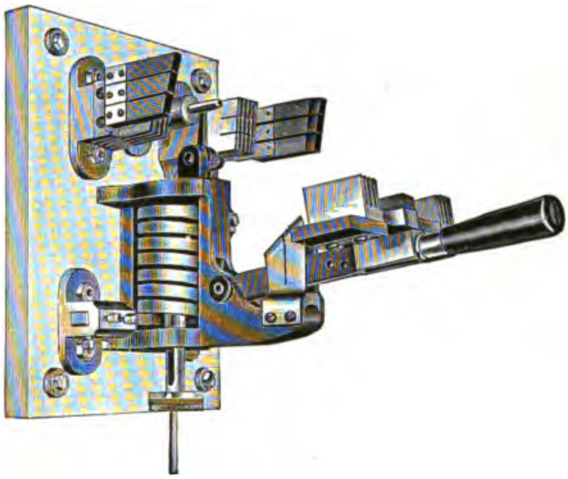

Fig. 138. Automatic Circuit-Breaker.

act again, and they can be set to open with a definite current. As already stated, however, fuses could probably be standardized to melt at a sufficiently exact limit.

In general it may be said that circuit-breakers are suitable for main circuits, or for those which are frequently overloaded, as in electric railway practice, and that fuses are applicable to branch circuits; but the latter are by no means confined to this use, since they are employed almost exclusively in the majority of incandescent-lighting plants. Circuit-breakers are usually preferable on switchboards.

CHAPTER XXIII.

ELECTRICAL MEASURING INSTRUMENTS.

THE subject of electrical measurements is one which should be treated in elementary and general works, or in those devoted to it. But, like the principles of electricity, it usually forms a large part of almost every special treatise as well; although, as already stated, it would seem that these subjects are preparatory to, and not part of, the study of any particular branch. It will therefore be sufficient in the present case to briefly consider the various classes of instruments and their applicability to electric-lighting purposes.

Classification. — The most important types of electrical measuring instruments may be subdivided as follows: —

1. *Ordinary galvanometers.* — Coil acting upon permanent magnet.
2. *Electromagnet devices.* — Coil or electromagnet acting upon soft iron.
3. *Electrodynamometers.* — Two coils acting upon each other.
4. *D'Arsonval instruments.* — Action between coil and magnetic field.
5. *Electrothermal devices.* — Heat generated by current produces expansion or other effect.
6. *Electrostatic instruments.* — Mutual action of two charged bodies.
7. *Electrochemical devices.* — Electrolytic effect of current.
8. *Miscellaneous instruments.* — Repulsion and other peculiar effects of alternating currents.

Galvanometers. — Until within about ten years, practically the only instruments used to measure electric current were simple galvanometers, consisting of a permanently magnetized needle, caused to deflect by passing the current through a coil placed around the needle.

The well-known Thomson reflecting galvanometer still remains the most sensitive means of detecting very feeble currents; but for almost all other uses, galvanometers have been superseded by volt- and amperemeters, and other more practical forms of instrument.

The extreme sensitiveness of the Thomson galvanometer is due to five facts: First, the coils usually contain a great many turns of wire; second, they are close to the needle; third, the latter is hung on a single fiber of silk; fourth, the deflection is enormously magnified by employing a beam of light reflected from a mirror; and fifth, the directive force of the earth's magnetism, which opposes the deflection, is neutralized by the use of astatic needles, by a magnet mounted over the galvanometer, or by both. Its principal applications in electrical engineering are measuring the resistance of the insulation of circuits and apparatus, and locating faults in the same. Ordinarily the resistance of insulation has a value of many megohms, consequently it requires a very sensitive instrument to detect the minute current which would flow through such a high resistance. On the other hand, this delicacy is unnecessary, and, in fact, very undesirable, if stronger currents are to be measured.

Furthermore, these galvanometers are disturbed by the slightest vibration, or by any variation in magnetic conditions, as, for example, when a dynamo is started or stopped, even if it be a hundred feet away; the usual result being that the zero point, as well as the deflection corresponding to a given current, are continually changing. Vibration may be taken up by supporting the instrument on springs, or preferably on a heavy metal or stone slab resting upon a cushion of rubber, feathers, or other soft material. The magnetic disturbances may be kept away from a galvanometer by surrounding it with a vertical iron cylinder, the ends of which are covered with iron plates or not, depending upon the intensity of the local magnetic field. But, in any case, holes may be made in the cylinder for observation, etc. These precautions are particularly necessary in an electric-light plant, where vibrations and stray lines of force naturally predominate, and where, in fact, it is almost impossible to entirely eliminate the difficulties which they cause.

The D'Arsonval galvanometer differs from the preceding in the fact that the deflecting part consists of a coil of wire, through

which the current is passed, the coil being hung in a field produced by a permanent magnet. Compared with the Thomson instrument, this possesses the great advantage that it is free from ordinary magnetic disturbances. For example, it is practically unaffected by a dynamo at a distance of ten feet. It is also less susceptible to vibration, because it is not so delicate, the moving part being much heavier and suspended by a fine wire, instead of by a silk fiber. As might be expected, these same facts render this form far less sensitive than the other. But it is well adapted to ordinary resistance determinations by the Wheatstone bridge or fall of potential ("drop") methods. When arranged for ballistic use, it is also suitable for magnetic and capacity measurements. In short, it may be employed whenever the available current is not less than about .000,000,1 ampere, whereas high-resistance Thomson galvanometers are made to give an appreciable deflection with only .000,000,000,1 ampere, or about one-thousandth as much.

These and other forms of testing apparatus should be put in a small room by themselves in a central station of any considerable size, being quite different in their functions from the regular ampere- and voltmeters, etc., which are placed on the switchboard for measuring the regular output of current. The matter of testing insulation and locating faults will be treated in Volume II. in connection with the subject of electrical distribution.

Principles of Ampere- and Voltmeters. — In most cases there is no essential difference between these two kinds of instrument. For example, a galvanometer used to measure current is also capable of acting as a voltmeter, provided the resistance in its circuit remains constant, because the current which flows through it is directly proportional to the voltage. Similarly, any voltmeter which allows current to pass through it can be calibrated to indicate amperes as well as volts. Ordinarily, however, an amperemeter is made with as low resistance as possible, since it is placed directly in the main circuit, and it is important that the loss of energy ($= C^2R$) shall be a minimum. Conversely, the resistance of a voltmeter which is connected as a shunt to the generator or circuit ought to be as high as possible, in order that the current taken by it shall be insignificant. Nevertheless, an ordinary amperemeter may be calibrated as a millivoltmeter, because there

is a certain voltage corresponding to each value of the current, that is, $V = CR$. In an analogous manner, almost any voltmeter (not electrostatic) can be converted into a milliamperemeter, since $C = \frac{V}{R}$.

Electromagnetic Amperemeters depend upon the principle that a current tends to induce magnetism in, and exert force upon, a piece of iron. One of the simplest forms is the Westinghouse amperemeter, shown in Fig. 139. It consists of a core, made up of a bundle of soft iron wires suspended from one end of a lever, which latter also carries the pointer. The core hangs within a coil, that consists of only three turns of very large wire in the type represented, this being sufficient with a current of 300 amperes. The main current traverses the coil, and draws the core downward, causing the pointer to be deflected over the scale. The instrument is leveled by means of the small plumb-bob on the right, and the force resisting the deflection is adjusted by moving the counter weight on the lever which supports the core.

Fig. 139. Westinghouse Amperemeter.

This particular form is intended for direct currents; but it is also adapted to alternating current by laminating the core, or by making it of fine iron wires, insulated from each other to prevent the circulation of induced currents. The same principle can be applied to a voltmeter by winding the coil with many turns of fine wire to obtain a high resistance for the reasons already explained on page 416. Resistance may also be put in series with the coil.

A great many modified forms are made according to the same

general principle, one of which is the well-known "pendulum ampere meter" used in many Edison plants. This consists of a coil in the form of the arc of a circle, which draws into itself a similarly shaped core that swings on a pivot.

The advantages of these electromagnetic instruments are their simplicity and cheapness. Their disadvantages are the fact that they do not indicate definitely near the zero point; and for direct currents the hysteresis of the iron core causes the reading for a given current to be lower when the latter is increasing than when it is decreasing. (See page 271.) This error is not material in a station or isolated plant amperemeter; but for a voltmeter, or for accurate measurements, it is too large to be neglected.

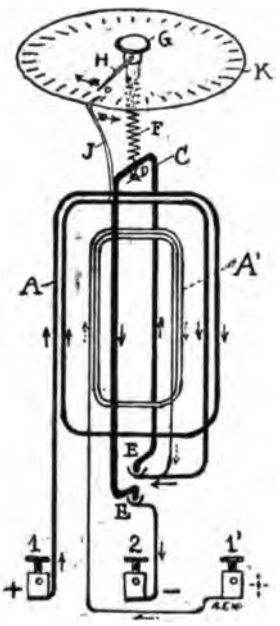

Fig. 140. Diagram of Siemens Electrodynamometer.

Electrodynameters. — One of the oldest and simplest of these is the Siemens type, represented in Fig. 140, which comprises the fixed coil *A*, and the movable coil *C*. The latter is large enough to surround the former, the two being placed so that their planes are perpendicular to each other. The movable coil is hung by a thread, or supported on a steel point, electrical connection being made to it by mercury cups, *EE*. The current is sent through the two coils in series, which tends to turn the movable one into the same plane as the other. This force is balanced by a torsion spring, *F*, that is twisted in the opposite direction with a thumbscrew, *G*, through a certain angle, as indicated by a pointer, *H*, attached to the screw. The mutual force between the coils is proportional to the square of the current, and the force is in direct ratio with the angle of torsion; hence the current varies as the square root of that angle. The instrument is calibrated, or provided with a table which gives without calculation the number of amperes corresponding to the various angles. The extra coil, *A'*, consists of a greater number of turns, and is used to measure small currents, connection being made by the binding-post, 1', instead of 1.

The Kelvin (Thomson) ampere balance, which depends upon the same principle, consists of two flat coils, *AA*, mounted like scale-pans upon the ends of a lever. These coils are acted upon by fixed coils, *CCCC*, placed above and below them, the force being balanced and measured by weights. The current passes through all of the coils in series as indicated.

Electrodynamometers are very accurate and constant, since there is no iron present to cause hysteresis; and they are applicable to either direct or alternating currents. They are, however, somewhat inconvenient to use, it being necessary with the forms described to either twist a spring or move a weight, and the force, being proportional to the square of the current, is extremely feeble with small currents, and excessively strong with large ones; consequently the accurate range is quite limited. This objection does

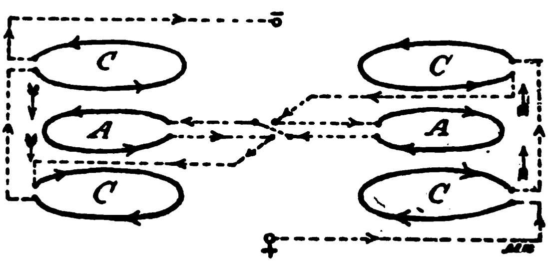

Fig. 141. Diagram of Kelvin Ampere Balance.

not apply when this principle is employed in wattmeters, which will be described later in the present chapter.

Weston Ampere- and Voltmeters resemble the D'Arsonval galvanometer in general principle. They are constructed, however, in a much more convenient and durable form; and their perfection in design and workmanship is such that they are sufficiently accurate not only for practical use, but also for almost any laboratory test. The deflecting part consists of a coil of fine wire wound on a very light rectangular frame of aluminum or copper, mounted on pivots, and carrying the pointer. This coil is situated between the poles of a permanent magnet of horseshoe form. A fixed cylindrical core of soft iron is supported within the coil to reduce the reluctance of the air-gap. Two flat spiral springs are attached to the ends of the frame, and perform the double function of opposing

the deflecting force and conveying the current to the moving coil. The ampere- and voltmeters are the same in external appearance, and also in construction, except that in the former the moving coil is in parallel with a shunt through which the main current passes, and in the latter it is in series with a certain resistance.

The merits of the Weston instruments are accuracy, portability, freedom from disturbance by stray magnetic lines, practically unaffected by ordinary temperature changes, large range, uniform scale-divisions over entire scale, accurate readings can be made quite close to the zero point, very small consumption of energy. The above statements cover almost every desirable point in connection with electrical measuring instruments, except applicability to alternating as well as direct currents. For station use these ampere- and voltmeters are made in the form shown in Fig. 142, which is often provided with an illuminated dial consisting of a translucent scale lighted from behind by an incandescent lamp, the top of the latter being seen in the figure. These are placed on the switchboard, or at any other convenient point. A similar but smaller type is made for isolated plants, and a third style is the well-known portable instrument. All three of these forms are manufactured for various ranges, from those having scales graduated in millivolts, to those indicating 1,500 volts or more. This type not being capable of measuring alternating currents, another form is made for that purpose.

Fig. 142. Weston Voltmeter.

The construction and applications of the Weston instruments are very fully described in a series of articles by H. Maschke in the *Electrical World,* beginning March 26, 1892.

The Cardew Voltmeter is the most successful measuring instrument depending upon the heating effect of the current. In it the pointer is caused to revolve by the expansion and contraction of a fine wire through which the current passes. This device can be used with either direct- or alternating-currents; but it is somewhat clumsy, the tube which contains the wire being nearly three feet

long. It also consumes considerable energy, the current at full voltage being about one-third of an ampere. Even at 110 volts this involves a loss which is by no means insignificant if it continues twenty-four hours a day throughout the year, particularly if several of these instruments are used in a plant. Sometimes they are provided with resistance coils in series, to multiply their range, and are employed to measure high potentials of 1,000 volts or

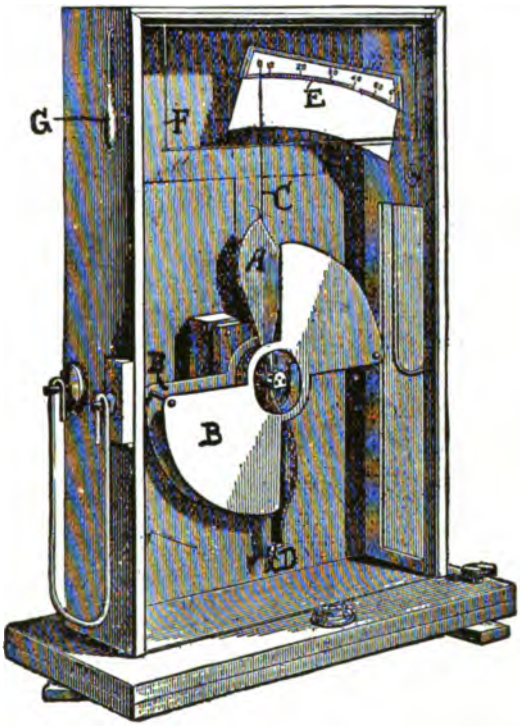

Fig. 143. Kelvin Vertical Electrostatic Voltmeter.

more, in which case the loss of energy is fully 300 watts, and becomes quite a large item.

Electrostatic Voltmeters. — In these instruments the mutual electrostatic attraction of two oppositely charged bodies is utilized to measure the difference of potential existing between them. The principle is identical with that of the electrometers used in laboratory work. One of the simplest forms is Kelvin's (Thomson's) vertical electrostatic voltmeter, consisting of two fixed metal-

lic plates, B, between which is pivoted a movable metallic plate, A, all three being parallel and vertical. The pair of fixed plates and the movable plate are respectively connected to the conductors between which the potential is to be measured. This causes the plates to become oppositely charged; and the movable plate is deflected in its own plane against the force of a weight attached to its lower part, and the position of the pointer C is read on the scale E. The attraction is proportional to the square of the potential difference; hence electrostatic instruments have a disadvantage similar to that explained in the case of electrodynameters. In fact, it is very difficult to obtain a practical device which will measure pressures of less than about 50 volts. But in electric lighting the potentials used are very rarely less than 100 volts, and are often as high as 1,000 volts or more; consequently these instruments are well adapted to the purpose.

The advantages of electrostatic voltmeters are: —

1. They are applicable to either alternating- or direct-currents.
2. They are extremely simple in construction and action.
3. They are cheap.
4. Their accuracy does not depend upon any condition which is likely to change.
5. They consume no energy, since no current flows through them.
6. They are absolutely free from magnetic disturbance.
7. They can readily be made for measuring potentials up to 25,000 volts, or even more.

The last advantage is so decided that this type is by far the best for very high potentials, and it possesses the six other advantages enumerated, even when employed for lower voltages. Up to the present time it has not been developed to the extent that its merits would seem to warrant, but it is now being perfected and applied more generally.

Electro-chemical Instruments are not commonly used for practical measurements, almost the only example being the Edison electrolytic meter, which will be described in Volume II., since it does not ordinarily form part of the generating-plant.

Special Alternating-Current Instruments. — Forms of ampere- and voltmeter have been devised in which effects peculiar to

the alternating current are utilized. For example, the action of repulsion, discovered by Professor Elihu Thomson, may be applied to purposes of measurement. These have no great advantage over the ordinary electromagnetic and electrodynamic effects, and are not only limited to alternating currents, but also in most cases depend upon the frequency.

Wattmeters. — If the Siemens electro-dynamometer described on page 418 is modified by winding one of the coils with a great many turns of fine wire, and connecting it to the circuit so that the current received by it shall be proportional to the voltage, the other coil being as before in the main circuit, and having the total current passing through it, the result is that the mutual action of the two coils depends upon both the pressure (volts) and current (amperes) of the circuit. In other words, the force exerted between them will be directly proportional to the product of the voltage and current, which is the number of watts.

For direct-current purposes a wattmeter is not very important; since all that is necessary is to read the potential from the voltmeter and the current in the amperemeter, and multiply the two numbers together to obtain the power in watts. But in alternating-current measurements the case is different; since there is a lag of the current wave with respect to the *E.M.F.* wave, if the circuit contains self-induction, as it almost always does. On the other hand, the effect of capacity is to produce a lead of the current; but in either case the "apparent watts" obtained by multiplying the volts by the amperes, as indicated in different instruments, is not the real energy. This must be multiplied by the *power factor*, which is the cosine of the angle of lag, in order to find the "true watts." It is difficult to determine this power factor; hence it is far more convenient to employ a wattmeter, which eliminates the error due to lag or lead so that the actual power may be read directly.

Recording Volt-, Ampere-, and Wattmeters. — These are employed in electrical generating-plants to make a continuous record of the output in volts, amperes, or watts. For example, a pen or other marking-device, is attached to the indicating part of a voltmeter, and a tape or circle of paper is slowly moved by clockwork so that a line is traced upon it showing the voltage at any time. These instruments require more positive action, and therefore

more energy, than the ordinary visual meters that merely move a pointer.

Ampere- and wattmeters are also made which integrate or sum up the total number of ampere-hours or watt-hours during a given period. These are chiefly used to measure the current supplied to each consumer, and they will be described under the head of Recording Meters in Volume II.

Regulating and fault-detecting apparatus, including rheostats, choke-coils, ground-detectors, and other similar devices and methods of using the same, which naturally belong to the subject of Electrical Distribution, will be treated under that head in Volume II.

The following are some of the most useful books on Electrical Measurements: —

GRAY, A., *Absolute Measurements in Electricity and Magnetism*, 2 vols., London, 1888 and 1893.

KEMPE, H. R., *Handbook of Electrical Testing*, Fifth Edition, London, 1892.

KEMPE, H. R., *Electrical Engineer's Pocket Book*, London, 1890.

MUNRO, J., and Jamieson, A., *Pocket Book of Electrical Rules and Tables*, London, 1896.

PRICE, W. A., *The Measurement of Electrical Resistance*, Oxford, 1894.

WEBB, H. L., *Testing of Insulated Wires and Cables*, New York, 1891.

CHAPTER XXIV.

LIGHTNING-ARRESTERS.

The various devices employed to protect electrical apparatus from lightning or atmospheric electricity are commonly termed lightning-arresters. This name, however, is not very appropriate; since they do not in any sense stop the discharge, but merely act to *divert* it, and convey it harmlessly to the ground.

Lightning-arresters are required wherever an electrical circuit, or any portion of it, extends out-doors; but they are obviously unnecessary if the conductors are wholly in-doors, underground, or submarime. The liability of an aërial wire to receive discharges of atmospheric electricity depends upon its length, its height above the ground, and its location, that is, whether it runs over hills or mountains; and certain regions are far more subject to this trouble than others. In England, for instance, its occurrence is comparatively rare and insignificant, whereas in the Rocky Mountains it is a matter of serious and almost constant difficulty.

The troubles which are likely to be caused in an electrical plant by atmospheric electricity are:—

1. Puncturing or charring of the insulation of the electrical machines, instruments, or conductors.
2. Melting off of wires, or fusing together of contact points.
3. Danger to persons.
4. Liability of starting a fire.

The first or second of these accidents will often almost ruin an electrical machine or instrument, and involve considerable time and expense in repairing. The last two, although of less frequent occurrence, may be even more serious in their results.

In many cases where a circuit is partly overhead and partly underground or under water, there is danger that the former portions will receive atmospheric discharges, which, running down

into the subterranean or submarine cable, will break through its insulation in order to escape to the earth or water. This may necessitate very troublesome and costly repairs.

The Principles of Lightning-Arresters. — Since the introduction of the telegraph about fifty years ago, the ordinary form of lightning-arrester consisted of a conductor connected to the ground, and brought close to, but not in contact with, the circuit before it reached the instruments, as indicated in Fig. 144. The atmospheric electricity coming in from the line, being of high pressure, would jump across the air-gap, and pass directly to the ground, this path having less impedance than that through the coils of the instruments *I* and *I*; whereas the ordinary working *E.M.F.* is not high enough to traverse the gap. Points are usually provided on each side of the gap to facilitate the discharge across it. This device is fairly satisfactory if only weak battery currents are used. But in the case of electric light, or other circuits carrying strong currents, there arises a new difficulty. It is found that the dynamo current follows the discharge, and establishes a short circuit after having once been started by sparks passing across the gaps *A* and *A*, as shown in Fig. 145.

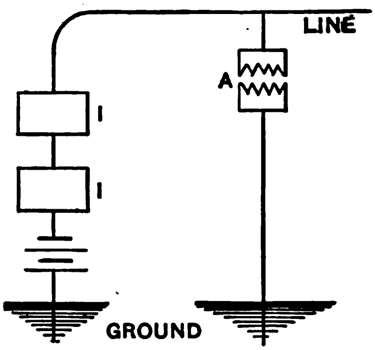

Fig. 144. Principle of Lightning-Arrester.

This would melt the dynamo fuses *F* and *F*, and interrupt the working current. With grounded circuits, an arc at one gap is sufficient to cause this trouble; but electric-lighting circuits, not being normally grounded, require arcs at both gaps to form a short circuit; but these are produced if the lightning comes in on both wires at once, which often occurs.

To obviate this difficulty, the spark-gaps were provided with automatic circuit-breaking attachments, which in their simplest form consisted of fuses in the discharge circuit, as indicated at *DD*. The fuses served to interrupt the short circuit without interfering with the working current; but these, having once melted, the plant was left unprotected from further discharges. Later the fuses were replaced by electromechanical devices, which should

not only stop the short circuit, but automatically readjust themselves for further operation.

The duty of the lightning-arrester, therefore, is to allow an indefinite number of static charges to pass freely to earth, and at the same time act as an effectual barrier to the flow of the current generated by the dynamo.

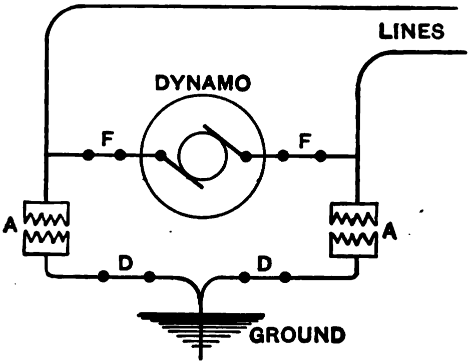

Fig. 145. Principle of Lightning-Arrester.

The numerous forms of lightning-arresters which have been brought out may be divided into the following classes, according to the means employed to interrupt the short circuit which tends to be established :—

1. Simple spark-gap, suitable only where working current is incapable of maintaining an arc across it.
2. Fuses in discharge circuit (as at *D*, Fig. 145).
3. Air-blast for blowing out arc.
4. Electromagnetic "blowing-out" devices.
5. Mechanical gap-lengthening devices.
6. Devices employing the so-called "non-arcing" metals.
7. Devices in which the arc is confined and smothered.
8. Arc dissipated by subdivision and distribution.
9. Arc prevented by introducing a considerable non-inductive resistance into the discharge circuit, which prevents the short-circuiting of the dynamo, but allows the high-tension charges to escape.
10. The presence of self-induction in the dynamo circuit opposes the passage of the discharge into the machine, hence coils are often inserted to add to the inductance of the machine.

Sometimes the arrester fails to interrupt the arc, and it becomes necessary to strike it out with a cloth or broom.

Comparatively few of these principles and forms of lightning-arrester have been applied successfully, and it will be sufficient to describe the most important of these.

The Thomson "Magnetic Blow-out" Lightning-Arrester. — Professor Elihu Thomson has ingeniously applied the action of a magnet upon a current to "blow out" the arc formed in lightning-arresters, switches, or similar devices.

It is well known that a conductor carrying a current tends to be moved or deflected in a magnetic field; and this is true whether the conductor be a wire or a conducting gas or vapor. Hence, if a lightning-arrester is provided with a magnet, placed so that the arc is formed in the field of the magnet, the arc will be repelled or "blown out," provided the direction of the magnetism and of the current is properly arranged.

Fig. 146. Thomson Lightning-Arrester.

One form of this arrester for alternating-currents is shown in Fig. 146, in which the spark-gap is between the two large plates in the center, and is in the field of the electromagnet, which is wound with copper ribbon. The lower binding-post is connected to the earth, and the two upper ones to the dynamo and line respectively. When the arc is formed by the discharge jumping from the line to the ground connection across the gap, it is forced aside and broken by the action of the magnetic field upon it. The same principle is applied to various forms of lightning-arrester for arc and other circuits.

The Keystone Arrester has been employed by the Westinghouse Electric Company for the protection of direct-current circuits for light and power.

This device operates to lengthen the spark-gap when the discharge takes place, the construction being shown in Fig. 147. The two lines or sides of the circuit are respectively connected to

the two upper binding-posts, the lower post being connected to the ground. A static charge coming in on either or both lines passes across the small gaps which exist between the carbon tips. If the dynamo current follows and forms an arc, the heat of the latter instantly expands the air in the inclosed chamber, which results in blowing out the two pivoted arms so that they swing against the bumpers at the top, as indicated by the dotted lines

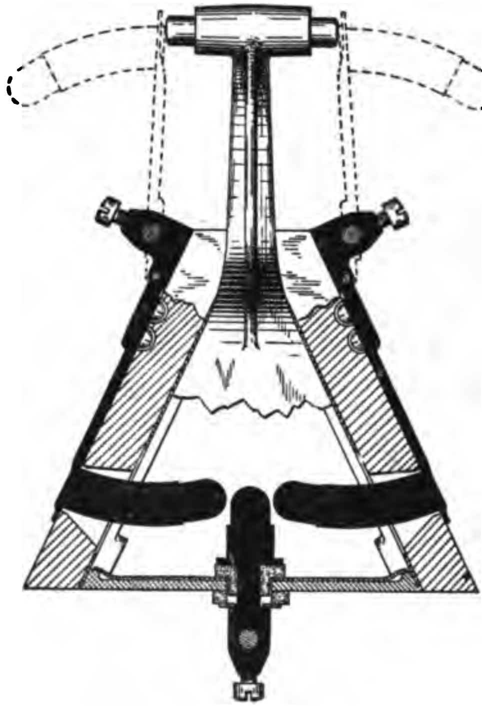

Fig. 147. Keystone Lightning-Arrester.

in Fig. 147. The arc is completely broken by the swinging out of the arms, and under the action of gravity they return to their normal position in readiness for a further discharge.

The Swinging Ball Lightning-Arrester is another type which acts to break the arc by lengthening the gap. The ball, which is connected with the ground, hangs normally in the position shown in Fig. 148; and a small air-gap exists between it and the metal piece below it, that is connected to the line by a branch wire.

When a discharge takes place and an arc is formed, the ball is thrown violently one side by the formation of vapor, and swings into the position indicated by dotted lines. This increases the length of the arc to such an extent that it goes out. Even if the arc should continue, the heat would rapidly melt away the wire upon which the ball hangs, which would thus act as a fuse in case of necessity, and could easily be renewed. This device is very simple and cheap, and has been used in large numbers with considerable success.

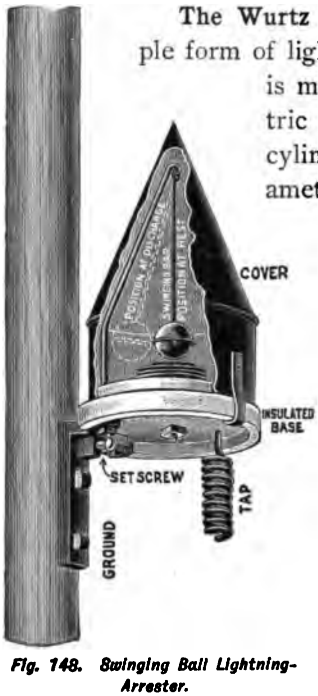

Fig. 148. Swinging Ball Lightning-Arrester.

The Wurtz "Non-arcing" Arrester. — A very simple form of lightning-arrester, devised by A. J. Wurtz,[1] is manufactured by the Westinghouse Electric Company. It consists of a number of cylinders (usually seven, each 1 inch in diameter and 3 inches long), placed side by side with air-gaps of $\frac{1}{64}$ inch between them. The cylinders are held in place by strips of marble or equivalent insulating material, as represented in Fig. 152. The cylinders are knurled or checkered, and thus present hundreds of confronting points for the discharge. The dynamo terminals are connected to the extreme cylinders, and the middle cylinder is connected to the ground (Fig. 149). The device is therefore double pole; that is, one arrester is sufficient for both sides of the circuit. When a discharge occurs, it passes across between the cylinders from either or both line terminals to the ground. If, for example, both lines discharge simultaneously to the ground, then sparks will occur at all six gaps, which will make a conducting path for the dynamo current, and completely short-circuits the machine, as is apparent in Fig. 149. But the arcs are destroyed as soon as

[1] "Lightning Arresters and the Discovery of Non-arcing Metals," *Trans. Am. Inst. Elec. Eng.*, March 15, 1892; "Discriminating Lightning Arresters and Recent Progress in Protection against Lightning," *Trans. Am. Inst. Elec. Eng.*, May 15, 1894.

formed, and the short circuit does not last long enough to produce any bad effects.

Mr. Wurtz considers this action (see papers cited above) to be due to the fact that certain metals are non-arcing. These metals

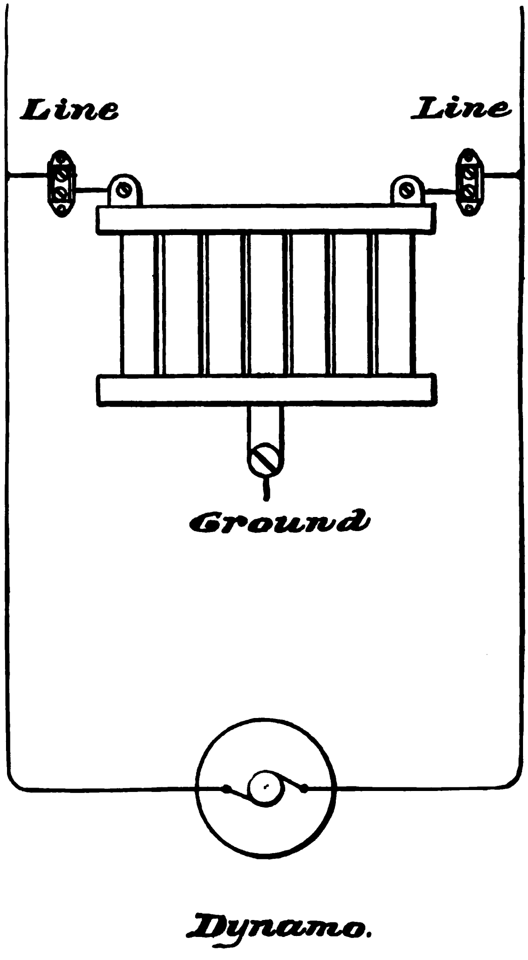

Fig. 149. Connections for Wurtz Lightning-Arrester.

are the zinc group, — zinc, cadmium, mercury, and magnesium; and the antimony group, — antimony, bismuth, phosphorous, and arsenic, according to Mendelejeff's grouping. He does not explain why such is the case, but it may depend somewhat upon the volatility of these particular metals. The sudden evolution of

considerable metallic vapor between the cylinders tends to blow out the arcs as well as to absorb the heat. This idea is borne out by the fact that Mr. Wurtz finds that the interruption of the arcs is more prompt and sure if the cylinders are very close together, i.e. $\frac{1}{64}$ inch, than if the gap be made greater. This indicates that confining the vapor tends to produce an explosive effect, which instantly extinguishes the arc, as it would in the case of a flame. It has also been suggested that the vapors of these metals may be poor conductors, perhaps due to the fact that at least some of them are monatomic, particularly at very high

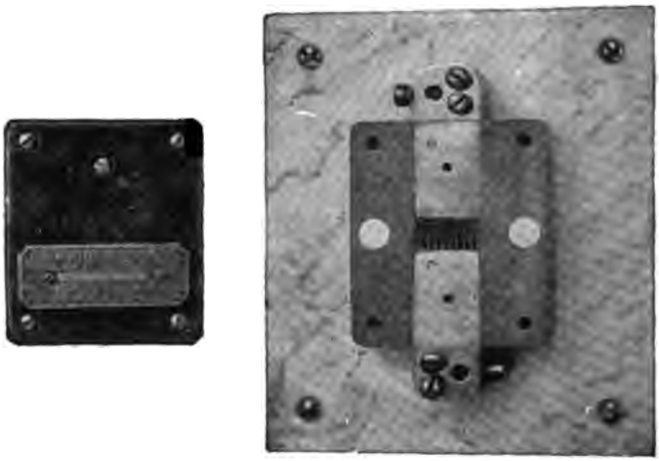

Fig. 150. Wurtz Direct-Current Lightning-Arrester.

temperatures. Whatever may be the explanation, it has been found by experience that this form of lightning-arrester is effective in the case of alternating-current lines, and that a large alternator may be repeatedly short-circuited by discharges passing across the gaps, without injury to the machine or to the arrester itself, the only effect being to very slowly burn away the cylinders at the gaps. Even this may be remedied by turning the cylinders so that they present new surfaces for the discharge. The material actually used for the cylinders is an alloy of zinc with just sufficient copper to enable it to be easily cast and worked.

This type of arrester is employed for alternating-current circuits, and also for certain arc systems (Westinghouse, Brush, and

Schuyler); but they are not applicable to direct currents of large volume, such, for example, as 110 and 220 volt incandescent lighting and 500 volt power circuits. For heavy direct currents the arc is too strong to be interrupted in this way, and some other form of arrester must be employed.

Another form of lightning-arrester invented by Mr. Wurtz, and manufactured by the Westinghouse Electric Company, operates upon the principle of smothering any arc which tends to be formed. It is shown in Fig. 150, and consists of two brass plates imbedded in a block of lignum-vitæ, and separated a distance of half an inch. The space between has narrow grooves burned in it as indicated in the figure, and it is over or through these that the discharge passes. This charred surface does not, however, act to any extent as a conductor for the dynamo current, since the resistance between the brass plates is over 50,000 ohms. If, now, the lignum-vitæ cap, shown on the left of the figure, be firmly screwed down over the charred grooves and brass plates, it will be impossible for an arc to form. The device allows static discharges to pass, but will prevent the flow of the large current which follows the discharge. This arrester is especially intended for railway circuits (500-volt), but it is also applicable to other direct-current circuits up to 1,000 volts. It also operates satisfactorily on 1,000-volt alternating circuits from smooth-core armatures; but with toothed-core armatures it breaks down, and short-circuits after a few discharges. Its extreme simplicity is a strong point in its favor.

The Tank Lightning-arrester, shown in Fig. 151, is also a form used by the Westinghouse Electric Company for direct-current circuits. It consists of coils of heavy wire, with several discharge circuits leading from different points of the coils to carbon electrodes immersed in a tank of running water. The coils are connected in series with the apparatus to be protected, and between the latter and the line. The tank is thoroughly grounded, and so divided by partitions as to insure circulation of the water. The resistance of the discharge circuits may be changed by varying the depth of immersion of the electrodes.

When lightning tends to follow the line to the apparatus, the coils of the arrester interpose an inductive resistance to its passage, while the several discharge circuits of very small induc-

tance offer comparatively easy paths to earth. The advantages of this device are — the discharge does not have to jump even the smallest air-gap; there is an opportunity for constant leakage of the static charge, which prevents the accumulation of a potential sufficiently high to break through the insulation of the dynamo, and at the time of discharge a short circuit of the dynamo is prevented by the resistance of the water.

The disadvantages of this arrester are that it allows a certain leakage of the dynamo to occur through it all the time, it is somewhat clumsy in form, and requires a stream of water to be kept

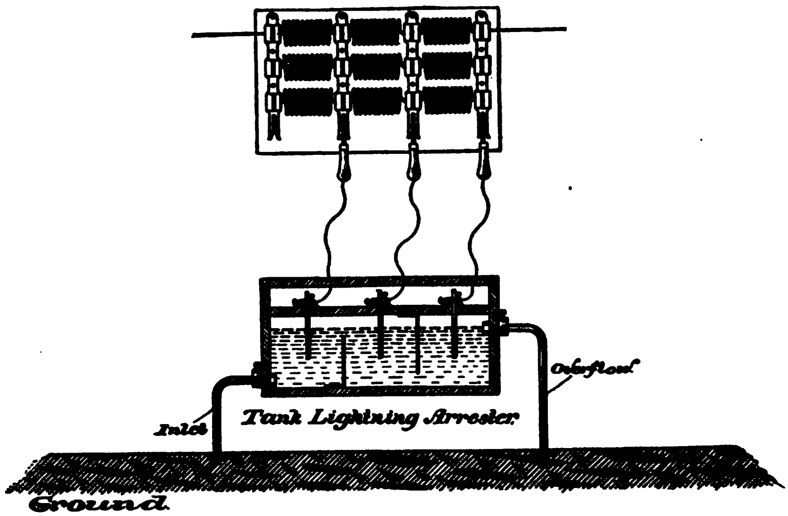

Fig. 151. Tank Lightning-Arrester.

running through it. These difficulties can, however, be reduced if the discharge circuits are disconnected by pulling out the plugs shown in the figure, when there is no danger of lightning discharges, during which time the flow of water may also be stopped.

This type is intended for electric railway circuits (500-volt); but it might be applied with slight modification to electric-lighting circuits, and it is interesting as being one of the few examples of lightning-arresters which steadily drain the static charge from the line without allowing it to accumulate, as already pointed out. This type of arrester, in which the line is permanently connected to the ground through a high resistance, has the great advantage

that the static charge runs away as fast as it is taken up by the line, and does not accumulate. One of the simplest arrangements of this kind consists of an ordinary plank, which is always kept wet by water dripping upon it. One end of this plank is connected to the line, and the other to the ground, so that any static charge by reason of its high potential will pass into the earth through the plank, but the resistance of the latter is great enough to prevent any serious leakage of the dynamo current.

Barbed Wire Lightning-Arrester. — This consists simply of a barbed wire laid immediately over the line throughout its entire length, or where it is particularly exposed. This wire is connected to the ground at various points, and protects the line by taking up and carrying to earth discharges which the line would otherwise receive. This is essentially different from other methods of protection from lightning in which the static charge gets upon the line, but is made to escape from it before reaching the apparatus. This plan is used in the case of the Lauffen-Heilbron power transmission line, and has also been employed in this country. It would seem to be one of the most effective means of protection; but it has the disadvantages of requiring an extra wire to be laid, with the necessary supports, etc. Mr. Wurtz * cites a case at Staten Island, N.Y., where this plan was successful, but states that at Telluride, Col., it was "a total failure." But the troubles from atmospheric electricity are so very great in Colorado, that this case may be considered as exceptional; and it is probably a fact that a guard wire over the line, the former being grounded at frequent intervals, will protect the latter under the conditions which exist in most places.

Location of Arresters. — Ordinarily lightning-arresters are placed on each overhead line or feeder after it enters the station, but before it reaches the switchboard or any apparatus. In the case of grounded circuits, one arrester is sufficient for each, as indicated in Fig. 144; but in the case of a metallic circuit, both lines should be provided with arresters, as shown in Fig. 145. Long lines are not sufficiently protected, however, by the station-arresters, and it is wise to place them on the line at not very great intervals, and particularly at points which are much exposed, or where there are sharp turns in the circuit. They should also

* *Trans. Amer. Inst. Elec. Eng.*, vol. xi., p. 386.

be arranged to protect transformers or other apparatus wherever they may exist on the circuit. Mr. Wurtz, in his paper and discussion on "Discriminating Lightning-Arresters,"* strongly insists upon the importance of placing arresters at numerous points, and argues that in this way the failure of one arrester may be retrieved by the others. He even uses groups or "banks" of lightning-arresters, placed one after another on the circuit; and

Fig. 152. Wurtz Lightning-Arrester Arranged for Outdoor Use.

also recommends the use of different kinds of arrester in some cases, for the reason that one type may be better suited to a discharge of a certain character. He further points out that disruptive discharges form nodal or neutral points along the line, at which there is little or no tendency to discharge. Hence a single arrester may utterly fail to act. Whether these views be accepted wholly or not, it is certainly a wise precaution to have

* *Trans. Amer. Inst. Elec. Eng.*, May, 1894.

more than one arrester to depend upon, since they are not very costly, and at least are not likely to do any harm.

The so-called line lightning-arresters for outdoor use are made very compact, and inclosed in a waterproof box, as represented in Fig. 152. If possible, arresters should always be placed directly on the main circuit, or have the circuit itself brought to them, instead of merely connecting them by a branch wire.

Ground Connections. — It is of the utmost importance that lightning-arresters should have very good ground connections, and the conductor from the arrester to the earth should be as short and straight as possible. In the case of a central station, a hole five or six feet square should be dug, as nearly as possible under the arresters, and deep enough to reach permanently damp earth. The bottom of this hole is covered with one or two feet of crushed coke or charcoal (about pea-size), over which is laid a copper plate of 20 or 25 square feet area, and not less than $\frac{1}{16}$ inch thick. In default of a copper plate, an iron plate or pipe of the same surface, and not less than $\frac{1}{8}$ inch thick, may be substituted. The ground wire, not smaller than No. 4 (A. W. G.), should be securely soldered across the entire surface of the plate. This plate should then be covered with one or two feet of crushed coke or charcoal, the remainder of the hole being filled in with earth. It is recommended that an additional ground connection be made to the water-main if accessible, thus providing two paths for the escape of the discharge.

The above arrangement is hardly necessary or practicable in the case of line or other subsidiary arresters, and the following ground connection will answer the purpose. A hole is dug two feet in diameter, and deep enough to reach permanently damp earth. A gas-pipe eight or ten feet long with open ends is then driven down, and a solid brass plug is screwed in the upper end, to which the ground wire of the arrester is soldered; the hole is then filled in with coke or charcoal, so that the surface drainage will increase the natural dampness of the earth.

The subject of protection against lightning must be admitted to be somewhat uncertain at the present time. While the general laws and phenomena are the same as those with which we are familiar in connection with artificial electricity, the enormous magnitude and intensity of atmospheric electrical actions introduce

effects which are not yet fully understood. Probably the greatest cause of confusion and disagreement has been the fact that there are so many *different kinds* of atmospheric electrical discharges. Indeed, it almost seems as if no two discharges act the same. This is due to difference of conditions, which a little more knowledge would doubtless correlate and explain. As an example of a phenomenon entirely unlike the ordinary idea of lightning, we may cite the statement of Mr. Wurtz:* "I have known circuits to become charged during *perfectly clear weather*, so that the discharges across a single lightning-arrester occurred at the rate of 100 to 140 a minute. It seems to me that the charging of the wire in this case must of necessity be due to conduction from the atmosphere."

* *Trans. Amer. Inst. Elec. Eng.*, vol. xi., p. 392.

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